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Geothermal Electric Power in Iceland: Development in Perspective

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INTRODUCTION

The main utilization of geothermal energy in Iceland is in thermal applications. It is now well known that there are many geothermal district heating systems in Iceland that supply hot water to residential, commercial and industrial buildings. Geothermal water and steam are also used in greenhouses and for processing purposes in industry. It could therefore be expected that geothermal steam be used extensively for the generation of electric power. This is however not the case and in the present paper it is hoped to put this situation into perspective. Although there is some geothermal electric power being generated in Iceland, the main emphasis has been on hydro-power of which the country is relatively well endowed with.

Iceland is a sparsely populated country with about 230,000 people living in an area of 103,000 km^2. Most towns and villages are located on the coast with about half the population living in the south-west of the country in the Reykjavík area. The first geothermal district heating service was started about 50 years ago in Reykjavík and now that service has been extended to the neighbouring towns. While 70% of the total population of Iceland enjoy geothermal space heating, about 50% are served by the Reykjavík system. The other 20% are served by about 25 public district heating services and various rural systems and individual hot springs around the country. It could be argued, that one of the reasons why such a large percentage of the population enjoy geothermal district heating, is the large percentage living in the Reykjavík area.

The energy resources of Iceland are relatively great and play an important role in the economy of the country. The organization of the energy industry must reflect this importance and it is therefore relevant to the topic of this paper to briefly describe the organization of the energy industry in Iceland in 1980. The Reykjavík District Heating Service, and most of the large district heating services around the country, are owned by the local municipal authority. These services both produce and distribute hot water to customers and are operated on limited-profit basis. Orkustofnun, the National Energy Authority, conducts all research and exploration of both hydro-power and geothermal energy. It is responsible to the Ministry for Industry (and energy) and acts as its main ad-

viser on matters of energy. Orkustofnun also operates a drilling company (State Drilling Contractors) that does all drilling in Iceland. On a small scale it also runs the State Geothermal Steam Supply that sells steam from one field. The main hydro-electric power generation company in Iceland is Landsvirkjun, the National Power Company. It produces the bulk of the electricity in Iceland and supplies wholesale the several large industrial users of electricity (more than half the total consumption) and the most important municipal distribution systems. Landsvirkjun is owned by the state and the city of Reykjavík. In addition there is the State Electric Power Works (Rarik) that operate several small hydro-power and other generating facilities, including the Krafla Power Station. The main function of this company is to distribute electricity in rural areas. In the north-west of Iceland there is a small state and municipally owned power company (West-Fjords Energy Company) that produces and distributes electricity, buying however some of it from the large producers. In the north-west of Iceland there is a hydro-power generating company (Laxá Power Works) that are owned 2/3 by the town of Akureyri and 1/3 by the state. This company also owns and operates the small Námafjall Power Station. There are three other municipally owned hydro-power companies in Iceland, but these are very small. There are three independent oil companies that import and distribute all oil products in Iceland.

EARLY DEVELOPMENTS

In the early history of Iceland the country was famous in Europe for the sulphur mined in its high-temperature geothermal areas. This mining continued on and off until the present century. Because steam and hot water were not used in the mining and refining process, this industry did not use geothermal energy directly. In the middle of the 18th century the first boreholes were drilled in geothermal fields in Iceland, the deepest being about 10 m. At a time when the Industrial Revolution was coming to a close, in the middle of the 19th century, there appear the first written articles in Iceland on the use of geothermal energy in steam engines. It was argued that our wool could be made 10 times more valuable if we used steam driven machinery for spinning and weaving. At that time wool was one of our main exports.

In all the history of Iceland, for more than 1100 years, hot springs have been used for bathing and washing. This utilization of geothermal energy was limited to individual hot springs until early this century when the first pipelines were laid for space heating and swimming pools. In 1928 modern drilling for geothermal energy in Iceland started. This was in a low-temperature field in Reykjavík where several shallow wells were drilled producing in total 15 l/s of 90-100°C water. This water was piped 2800 m to supply about 70 homes, one school and a large swimming pool in 1930. Since then great developments have taken place and now geothermal district heating plays a very important role in the economy of the country.

At about the same time as geothermal dristrict heating was being introduced in Iceland, the generation of electric power using geothermal steam was already under discussion. Small scale industrial utilization of geothermal steam was also initiated in 1930 for the purpose of pasteurizing milk. In the years that followed several schemes were started but the only significant utilization that materialized was the greenhouse industry. In 1944 the first steam driven engine was installed in a high-temperature field in Iceland. This was near Hveragerdi where several shallow boreholes had been drilled and were being used for various purposes. This first steam engine with generator was only run for a short time and produced sufficient electricity for just a few lightbulbs. Earlier the same year geothermal electric power generation and hot water production had

been the subject of debate in the parliament (Althing) and in 1945 the drilling rigs owned by the state were taken over by the now Orkustofnun. At the same time the first geothermal specialist was recruited and modern exploration and exploitation began. In 1946 the first steam turbine system was installed capable of generating 35 kW of electricity. It operated for only one year near Hveragerdi until a much larger diesel generator was installed in the town.

Extensive geothermal studies and drilling were carried out in the years that followed. Not only in the Hengill area, where the town of Hveragerdi is situated, but also in the Krísuvík area which is likewise located in the south-west of Iceland. In 1950 a feasibility study had been carried out for a 30 MW geothermal electric power plant to be located near Hveragerdi. It was estimated that the geothermal electricity would cost 40-50% more to produce than in a similar sized hydro-power station. Subsequently it was decided to build a second hydro-power station in the river Sog (it became operational 1953) to serve the electricity market of south-west Iceland, particularly Reykjavík.

Great advancement was made in the exploration and exploitation of geothermal energy in 1958 when a rotary drilling rig, with a depth capability of more than 2000 m, was bought to Iceland. From 1958-1961 it was used to drill 8 boreholes 300-1200 m deep near Hveragerdi. At that time the now National Energy Authority (Orkustofnun) and State Electric Power Works (Rarik) were one organization being leading in the exploration and other work undertaken in the high-temperature field near Hveragerdi. By 1961 the project design of a 15 MW (net output) geothermal electric power plant was completed. It was to consist of 4-5 production wells delivering steam at 3-3.5 bar gauge pressure to two turbo-alternators with direct contact condensers at 0.07 bar absolute pressure. The consulting engineers working with the Icelandic authorities were Merz & McLellan of London, England. It was concluded that the capital cost per installed kW was similar to that of hydro-power stations in Iceland of under 40 MW in output. The generation cost of electricity from both types of stations was considered comparable. The details of the proposed 15 MW station are given by Einarsson (1961). By the early 1960's it had become generally accepted in Iceland that the traditional fishing industry and agriculture would not be able to sustain reasonable economic growth and

that new industries had to be introduced. The view was that this had to be energy intensive industry on large scale such as aluminium smelting. At the same time it was clear that the most economic small hydro-power plants had already been built such that it would be adventageous to build large and more economic stations. Any plans to build small geothermal electric power stations were therefore easily pushed aside and in 1965-1966 it was decided to build a 210 MW hydro-power plant at Búrfell in the river Thjórsá. Simultaneously an agreement was signed with an international aluminium company to build a large smelter not far from Reykjavík. The generators of the Búrfell station were installed 1969-1972 and yet again hydro-power electricity had terminated plans to build a geothermal power plant.

ENERGY RESOURCES

Assessment

In the present paper an emphasis has been placed on geothermal electric power in Iceland in perspective of the general energy situation of the country. An important consideration in such a perspective must be the indigenous energy resources and their assessment. Recently, Orkustofnun has completed new assessment studies of both hydro-power (Tómasson 1981) and geothermal energy (Pálmason 1981). The main conclusions of these studies will be mentioned here, particularly the geothermal energy assessment.

Geothermal Energy

The geothermal areas in Iceland have been divided into low- and high-temperature areas (Bödvarsson 1961). The high-temperature areas are in the active volcanic zone laying south-west to north-east across Iceland and the low-temperature areas are on both sides of it. The two main low-temperature areas are in the south and west of Iceland at the periphery of the active volcanic zone, but other areas are widely distributed. In the low-temperature areas the temperature of the reservoir fluid in the uppermost 1000 m does generally not exceed 150°C while in the high-temperature areas it does, and is usually 200-350°C. There are about 600 hot springs in 250 low-temperature areas in Iceland and their natural flow has been estimated as 1800 l/s at an average temperature of 70°C. With all the drilling that has been conducted in the low-temperature areas to the present, the total production from the same areas has been increased to 4600 l/s or 155%. The average temperature of this increased flow is estimated as 80°C (Gudmundsson & Pálmason 1981). It should be emphasized here that the water produced in low-temperature areas in Iceland is used in thermal applications only and is the backbone of the district heating industry.

When it comes to the generation of geothermal electric power in Iceland, the high-temperature areas have to be used. The first attempt to assess the electric power generation capability of the high-temperature areas was that of Bödvarsson (1956), about 25 years ago. Several assessment

studies have since been conducted, the most comprehensive being that of Pálmason (1981). This study is based on the same methodology as used in the U.S.A. and Italy (Muffler & Cataldi 1978), but with several modifications to suit geological conditions in Iceland. There are 19 known high-temperature areas in Iceland and 9 potential areas. Figure 1 shows a map of Iceland and the location and name of the 28 high-temperature areas, within the active volcanic zone. Table 1 shows the main conclusions of the geothermal assessment study. The total size of the high-temperature areas is about 600 km^2. To arrive at an estimate of the electric power which the areas could possibly produce, it is assumed that 20% of the thermal energy of rock and water above 130°C down to a depth of 3 km are recoverable. This thermal energy is then converted to electricity with an efficiency of about 7-9%, depending on the known or expected temperature of the fluids produced. In total it is estimated that 3,500 MW-electrical can be produced for a period of at least 50 years. About 3,000 MW-electrical would be in known high-temperature areas.

An important consideration in the assessment of geothermal energy, is whether or not the resource is renewable or non-renewable. When considering geothermal energy in terms of geological time (-scale), it must be viewed as renewable, while in terms of utilization for the benefit to man, we probably have to consider it non-renewable. For the country as a whole, however, because our present needs are small in comparison to the resource, it could be argued that our geothermal energy is renewable for practical purposes. A further important consideration is that geothermal assessment does only indicate the thermal energy present in the ground, it does not say anything about the rate at which it can be extracted, namely the power. The only way to know that is by drilling and discharge measurements.

Hydro-Power

The first assessment of the hydro-power potential of Iceland dates back to about 1920 at a time when the early hydro-stations were being considered. About 40 years later the assessment was up-dated, increasing the estimate from 26 TWh/year to 35 TWh/year. In recent years, Orkustofnun and other organizations, have been re-evaluating the hydro-power

potential and now a new assessment has been published (Tómasson 1981). While the older estimates are based on specific schemes for harnessing the hydro-power, the new assessment is based on a systematic evaluation of the whole country. The main conclusion is that the "gross theoretical capability" amounts to 187 TWh/year. The available or usable capability is however much lower and is estimated as 64 TWh/year, with an associated installed capacity of 7,300 MW. These values do not take into consideration economical, except indirectly, and environmental issues. The usable hydro-power is however divided into four groups, that range from the most economical to marginal. In the years to come the large hydro-schemes in the highlands (first group) will be most economic with a generating capability to about 30 TWh/year or almost 1/2 the total potential of the country. The associated installed capacity corresponds to about 3,400 MW. Many of these schemes are being investigated at the present.

Comparison

It has been shown above, that the available geothermal electric power (energy) in Iceland amounts to 3,500 MW (for 50 years), if all the high-temperature areas of the country were to be used for that purpose, which is however unlikely. The hydro-power assessment shows that the installed electric capacity associated with the available hydro-power may amount to 7,300 MW (forever), which is more than double the geothermal value. Based on these studies, it seems only natural that hydro-power continues to supply the bulk of the electricity required in Iceland.

ENERGY MARKET

Overview

The energy market in Iceland is in many respects unusual in composition when compared to many other countries. The main reason for this is the large amount of hot water sold for space heating purposes. Another feature of the market is that for many years almost half the total energy consumption has been imported petroleum products, although the country has relatively great hydro-power and geothermal energy resources. In recent years great effort has been made in replacing oil-heating with geothermal district heating (Björnsson 1980). From 1973 the amount of heating oil used in Iceland has decreased by about 2/3 with the result that the total import of petroleum products has remained about the same although the use in other fuel sectors has increased.

When estimating the contribution of hydro-power, geothermal energy and imported oil to the total amount of energy delivered to customers in Iceland, it is difficult to find a fair basis of comparison. Electricity and hot water are a bit like chalk and cheese. One method is however represented in Table 2. It shows the amount of hydro-power electricity, geothermal water and steam above 5°C, and the lower heating value of all imported oil products. The method adopted for estimating the contribution of geothermal energy to the total amount of energy delivered to consumers, needs a comment. When dealing with geothermal water at temperatures below 100°C, the amount of energy extracted from that water depends on the lower temperature to which it is cooled. Water at 80°C cooled to 40°C gives double the thermal energy of water cooled to only 60°C. In the cold climate of Iceland it has been found convenient when compiling energy statistics to use the average annual air temperature of 5°C as the lower reference temperature. Table 2 shows that in 1979 hydro-power supplied 18%, geothermal energy 38% and imported petroleum product 44% of the total energy delivered to customers. It should be noted in Table 2 that about 45% of the total energy delivered to customers is for space heating. If the actual energy cunsumption of customers is estimated, taking into account the efficiency of utilization, the three energy sources (hydro, geothermal, petroleum) contribute about 1/3 each to the total consumption (Ragnars 1980).

Electricity

A brief overview will now be given of the electrical energy industry in Iceland in 1980 as published in the annual statistical report (Orkumál) of Orkustofnun. The total production of electricity amounted to 3,143 GWh of which 3,053 GWh or 97.2% was from hydro-power stations. Geothermal electric power stations produced 45 GWh (excluding own use) and oil-fired and diesel stations also 45 GWh. More than 1/2 the electricity or 56.7% was used in energy intensive industries (aluminium 40.9% and ferrosilicone, ammonia etc. 15.8%) while 43.3% was used for general purposes. At the end of 1980 installed generating capacity of all public electric power stations was 670 MW of which 542 was hydro-power, 12 MW geothermal (see later) and 116 MW oil-fired or diesel. Figure 2 shows the increase in total installed electric generating capacity from 1920-1980 and the associated amount of electricity produced.

Petroleum

A few words about the petroleum products imported to Iceland in 1980. The total fuel use amounted to 542,083 tonnes, being 10.4% less than in 1979. Of this 43% was distillate fuel for fishing vessels mainly, but also for space heating, industrial use, transportation and the generation of electricity in small diesel stations. Residual fuel was 32% being used for trawlers with large engines and also in industry. Gasoline for motor transport amounted to 16% while jet fuel, aviation gasoline and kerosene added up to 9%.

Geothermal

More details will now be given about the geothermal energy market in Iceland. For convenience, the contribution of low- and high-temperature areas will be dealt with separately. It must be stated here, that the statistics for geothermal energy production and utilization are not as well developed as for electricity (predominantly hydro-power) and imported fuels. Figure 3 shows the utilization of geothermal energy in Iceland in 1980.

An extensive survey of low-temperature geothermal energy utilization in

Iceland in 1980 is that of Gudmundsson & Pálmason (1981). Only the main result of this survey will be presented here. Table 3 shows the geothermal power associated with the utilization of hot water for space heating, greenhouses, swimming pools, industrial drying and fish culture. The thermal power values represent the production capacity required to satisfy the maximum demand during the year. In Reykjavík the maximum demand for space heating was in February when the Reykjavík District Heating Service produced from its low-temperature fields almost 3/4 of the total values showed in Table 3. It was however stated above that the Reykjavík District Heating Service provided about 50% of the total population of Iceland with geothermal district heating. This difference (50% vs. 3/4 or 75%) is mainly explained by the fact that several district heating services are operated in high-temperature areas, namely Svartsengi, Hveragerdi and Námafjall (Reykjahlíd village), but also in Vestmannaeyjar where the heat source is a recent lava flow. The load factor for the Reykjavík District Heating Service is about 50% such that the low-temperature geothermal energy produced in Iceland in 1980 was approximately 17,000 TJ, 15,000 TJ and 12,000 TJ above 5°C, 15°C and 35°C reference temperatures, respectively. Table 3 shows that almost 90% of the low-temperature waters produced in Iceland are used for the heating of residential, commercial and industrial buildings.

An extensive survey of the utilization of high-temperature geothermal energy in Iceland is not available. For the purpose of the present paper, information from the internal files and reports of Orkustofnun were therefore used. This data is more difficult to present in a meaningful way than low-temperature geothermal energy, because geothermal steam is used in both thermal (direct) and electrical applications. It will however be attempted here because the focus of the paper is geothermal electric power. The results presented will only be approximate.

At the end of 1980, high-temperature geothermal energy was used in 4 areas in Iceland, if small experimental units are excluded. Table 4 shows these areas and the main details. For each high-temperature area, there is shown the number of boreholes drilled and how many are capable of production. The thermal power is divided into installed and used. The former represents the maximum thermal power which the production boreholes are capable of delivering at present back pressures or lower. This

thermal power is calculated on the basis of condensing all the steam and cooling the total borehole discharge (steam and water) to 100°C - perhaps not a realistic representation of the data, but simple. The used thermal power, on the other hand, is the actual thermal power consumed in the relevant direct application. At Svartsengi it is the maximum thermal power consumed for space heating, in Hengill it is the thermal power used for space (10 MW) and greenhouse (15 MW) heating in Hveragerdi, while the Námafjall application is for industrial drying. The last column in Table 4 shows the name-plate capacity of the 3 geothermal electric power stations in Iceland (see later). The geothermal steam used for these power-plants is included in the installed thermal power shown in Table 4.

It is of some interest to estimate the thermal power associated with all (low- and high-temperature) direct applications in Iceland. Table 5 shows the approximate thermal power used in all direct applications in Iceland in 1980. Experience in Iceland shows that low-temperature waters used for space heating are discharged at 35-40°C on average. The total geothermal power consumed in direct applications in 1980 amounts therefore to 818 MW-thermal. Assuming a load factor of 50%, corresponds to about 13,000 TJ or 3,600 GWh. Again, this does not include the geothermal energy used for generating electricity. It was stated above, that 45 GWh (net) of geothermal electricity was produced in 1980.

EARTH HEAT ELECTRIC POWER

In the early 1960's, when it became clear that a 15 MW geothermal electric power plant near Hveragerdi would not be competitive with the very much larger hydro-schemes under consideration, further work on the project was abandoned. Additional reasons for the lack of interest in the Hveragerdi scheme, were problems of both geothermal and technical nature. The enthalpy of the steam-water mixture produced in the boreholes was rather low, 900 kJ/kg being a representative value, corresponding to a reservoir temperature of about 215°C. This meant that a large quantity of steam and water had to be produced to generate the electricity, resulting in a disposal problem. A small river flows through the field but it would not be able to receive all the waste fluids without some environmental damage, even if a large cooling pond was to be provided. This, and expected calcium carbonate ($CaCO_3$) deposition in the boreholes, did not favour building a power plant near Hveragerdi. The interest in geothermal electric power in Iceland was however aroused again when temperatures of 260-280°C were encountered when drilling in Námafjall 1965-1966.

Now there are 3 geothermal electric power plants in Iceland. These are at Námafjall and Krafla in the north-east and at Svartsengi in the south-west. The Námafjall and Krafla areas are not far from each other, only 7-8 km. Figure 4 shows the two geothermal areas and the active fissure swarm associated with the tectonic movements and volcanic activity of the Lake Mývatn region (Stefánsson 1981). The Svartsengi area is on the Reykjanes peninsula where there are several other high-temperature areas. Figure 5 shows a map of the peninsula and the main geothermal features (Georgsson 1981).

Thórhallsson et al. (1979) have recently reported on detailed inspections of the 3 geothermal electric power plants in Iceland. The Krafla power plant, both the steam supply system and the steam turbine, was inspected especially for the purpose of assessing corrosion, erosion and deposition problems. The other two stations were inspected for comparison, although the Svartsengi plant has been looked at several times since it was installed. Most of the detailed information presented here, about the steam turbines in the 3 stations, is taken from that report.

The main technical specifications of the 3 geothermal electric power stations in Iceland are presented in Table 6. The total rated capacity amounts to 41 MW. The Krafla power station, however, has never operated on full load because not enough high-pressure steam has been available. Its maximum load was initially 6-8 MW but has now reached 11-12 MW. In the Svartsengi station there are two 1 MW units and one 6 MW unit, in total 8 MW. All of these have been run at full load, as has the Námafjall station. Table 7, which is based on the Orkustofnun annual statistical report, shows the electricity produced in the 3 geothermal electric power stations in Iceland 1975-1980.

NÁMAFJALL

Development

Around 1950 a few shallow wells were drilled in the east part of the Námafjall area in connection with experiments to produce sulphur from hydrogen sulphide (H_2S) in geothermal steam. These plans did not materialize but somewhat later rich deposits of diatomite were discovered in the nearby Lake Mývatn. Drilling in the west part of the Námafjall area was started in 1963 and in 1966 the first production well was drilled. It supplied the diatomite processing and drying plant that was commissioned in late 1967. The development of the Námafjall area has been described by Ragnars et al. (1970).

Feasibility

In a study by Einarsson (1967) the feasibility of building a 5-10 MW non-condensing geothermal electric power station in Námafjall was investigated. The study indicated that such a scheme would be an attractive way of meeting the increased load in the north-east part of Iceland, in smaller steps than would be economically feasible in hydro-power stations. An important consideration at that time was also the felt need of gaining experience in operating a geothermal electric power plant. In 1968 it was decided to build a small atmospheric exhaust plant at Námafjall and in 1969 it became operational. By 1971 enough steam had been secured for both the power plant and the diatomite plant and then onwards the Námafjall station was in full operation.

Power Station

The turbine-alternator is a British Thompson Houston (BTH) industrial set built in 1932. It was bought second-hand, but some alterations were made on it 1968 when it was installed. The steam turbine itself is of the simplest possible type with one Curtis wheel. In 1971 the wheel was replaced with a new one to increase the output and to change the material of construction to make it more suitable for geothermal steam. The rated capacity is now 3 MW and the material used 12-14% Cr-steel. In 1974 the old alternator was destroyed and a new one from ASEA (in Sweden) installed.

At the same time it was found that the shroud bands on the first row of blades were damaged and had to be repaired. Every year some silica deposits have to be cleaned from the inlet nozzles of the steam turbine. This has been caused by some carry-over of water from the steam-water separators. After almost a decade of operation, the condition of the steam turbine at Námafjall is good. There has been some pitting corrosion and erosion of the first row of blades, but not serious. The materials of construction are similar to the 30 MW steam turbine at Krafla, except the labyrinth seals are stainless steel at Námafjall.

Geothermal Steam

Ten boreholes had been drilled in Námafjall by the end of 1975. They ranged in depth from 340 to 1800 m and were spaced at about 100 m apart. The production field is at Bjarnarflag on the west side of the area. Arnórsson (1977) has reported on the chemistry of steam and water discharged from boreholes 4-9 during 1970-1976. The other wells, 1-3, were not productive. All these had been drilled by 1970, the 10th in 1975. The highest measured temperature reported was 290°C in borehole 7. Wells 4-9 produced in total about 200 kg/s of steam and water with an enthalpy of 1100-1200 kJ/kg. Arnórsson (1977) reported that the average temperature of the fluids entering the boreholes at depth, had decreased by 30-45°C during a 5 year period. There were also changes in the chemistry of the fluids. It was postulated that these changes were caused by the onset of flashing in the reservoir as exploitation progressed.

In 1979-1980 two more boreholes were drilled in Námafjall. By then some of the older boreholes had been destroyed due to volcanic activity near Krafla. It appears that magma, from the fissure swarm extending to Námafjall, entered the area and caused increased surface activity. In September 1977 borehole 4 even produced fresh volcanic ash and the hydrogen sulphide (H_2S) associated with this event caught fire! In the winter of 1977/1978 the steam production came to a minimum from the boreholes, and in July 1978 the steam turbine and associated equipment was removed from the Námafjall Power Station. It was not until October 1980 that it became operational again, now with the two new boreholes on line. Temperature and other measurements in wells 11 and 12 have shown, that the geothermal reservoir in the Bjarnarflag field has changed due to the magmatic

activity. The upper part of the reservoir has become colder, probably due to more rapid infiltration and circulation of cold water as a result of increased fracturing near the surface. The temperature of the ground-water in the area has increased 10-20°C in some locations. At the same time the lower part of the reservoir has increased in temperature such that wells 11 and 12 produce predominantly steam.

At the end of 1980 two wells (11 and 12) produced high pressure steam for the diatomite plant and the Námafjall Power Station. Borehole 11 produced 29 kg/s at 19 bar-g pressure of steam-water mixture with an enthalpy of 2400 kJ/kg. The amount of 11-12 bar-g steam produced in the steam-water separator was 23 kg/s. Borehole 12 produced 22 kg/s at 16 bar-g pressure of steam-water mixture with an enthalpy of 2300 kJ/kg. In the separator at 11-12 bar-g it produced 16 kg/s of steam. The diatomite plant received about 12 kg/s of 10 bar-g saturated steam and the electric power plant about 17 kg/s of 9 bar-g steam. In December 1980 the station generated about 2.5 MW and because this power is lower than the rated capacity it is concluded that with age the efficiency has decreased due to wear and tear. Borehole 4 at Námafjall is the only old well that still produces. In total it is capable of about 10 kg/s of steam-water with an enthalpy close to 1000 kJ/kg. About 2 kg/s of low-pressure steam from this borehole is used to directly heat fresh water for district heating in the Reykjahlíd village by Lake Mývatn.

Recent measurements of the gas content and composition of the 9-12 bar-g steam produced at Námafjall are not available. Steam and water samples have however been taken at the well-head of boreholes 11 and 12. To illustrate the likely gas composition of the steam, it was calculated from the chemical analysis. Table 8 shows the estimated gas composition of the saturated steam produced from borehole N-11 (Námafjall) when allowed to flash down to 180°C or 10 bar-g pressure. The total gas content is estimated as 0.2% by weight.

The steam-water mixture from the boreholes is piped in two-phase from two Webre-type cyclonic separators. These have (safety) valves that are adjusted to open if the pressure increases above the operating pressure of 11-12 bar-g. In this way the excess steam produced is vented to the atmosphere. The high pressure water is discharged to concrete silencers

that separate the boiling water and steam at atmosperic conditions. The water collects into a surface pond and then percolates into the ground. In the almost 15 years that geothermal steam has been exploited in Námafjall, the disposal water has not caused any problems.

Drilling

The boreholes drilled in high-temperature geothermal fields in Iceland now, are very different from the boreholes drilled 10-20 years ago. This is to be expected because drilling practices and borehole design have developed through the years and been adjusted and changed to meet the requirements in each geothermal field. The boreholes drilled in Námafjall 1979-1980 are similar to the most recent wells drilled in Krafla. Ragnars & Benediktsson (1981) have described the drilling of a typical 2000 m deep borehole in Námafjall. The drilling and casing of this borehole will now be described, and the cost data for well number 11 in Námafjall presented.

The drilling is initiated with a cable-tool rig that drills a 22" hole to a depth of about 50 m. This hole is cased (and cemented) with a 18 5/8" surface casing (78 lbs/ft, St 52 welded). Then, rotary drilling starts with a 17 1/2" bit down to a depth of about 300 m. The drill-rig used at Námafjall and Krafla is a Gardner Denver 700 E diesel/electric, the largest in Iceland, capable of drilling to a depth of about 3600 m. A 13 3/8" anchor casing (68 lbs/ft, J55, buttress) is then lowered and cemented. Drilling continues with a 12 1/4" bit down to 700-1100 m, depending on the geological conditions. This hole is cased with a 9 5/8" production casing (43.5 lbs/ft, J55, buttress) which is cemented with the following mixture: Portland cement 100 kg, Silica flour 40 kg, Perlite 4 kg, Bentonite 2 kg and Retarder 0.2 kg. This mix is also used for cementing the anchor casing. In Krafla the production casing is 900-1100 m, while in Námafjall it is 600-700 m. When the production casing has been cemented the borehole is drilled to about 2000 m with a 8 1/2" bit and then a 7" slotted liner (26 lbs/ft, J55, buttress) is hung from the lower end of the production casing and down to the bottom.

The main valve is connected to the anchor casing and there is an expansion-spool-piece for the production casing to expand into. In Námafjall and Krafla the main valves are 10" ANSI 900 (WKM gate-through-conduit)

and there are also 10" DIN 25 kg valves (Sigma, gate) for back-up and general use.

Ragnars & Benediktsson (1981) give the actual cost of drilling well 11 in Námafjall in the middle of 1979. The borehole is 1923 m deep, cased with 13 3/8" to 280 m and 9 5/8" to 620 m. The 7" slotted liner extends to the bottom. The drilling time was 33 days. Table 9 shows the actual cost and how it was divided between the main cost items. It must however be appreciated that the total drilling cost can vary appreciably between geothermal fields. The boreholes drilled in Krafla are more expensive than in Námafjall, with a total cost of almost one million dollars. In the south-west of Iceland in Svartsengi, the boreholes are however less costly.

Organization

The geothermal field in Námafjall was developed and is operated by the State Geothermal Steam Supply at Orkustofnun. This company delivers the 9-10 bar-g saturated steam to the diatomite processing and drying factory and the geothermal electric power plant. The diatomite factory is a joint venture of the state and the Johns Manville Corporation in the U.S.A. The power plant is owned and operated by the Laxá Power Works which is the electricity generating company (mainly hydro-power) for the town of Akureyri area. The diatomite factory and the steam supply sompany have an agreement about the steam price, which is then also used for the steam delivered to the power plant. The present agreement is such that the steam price depends 60% on the general inflation (construction cost index) in Iceland and 40% on the rate of exchange of the U.S. dollar. In October 1980 the price was exactly 1$/tonne which is however considered too low to cover the steam production cost.

KRAFLA

Development

About 10 years ago there were plans to increase the electricity production capacity of the hydro-power station in the river Laxá in north-east Iceland. The plan was to quadruple its then capacity of about 12 MW electrical. The Laxá Power Works operates this station and the main transmission line to the town of Akureyri, the largest town in north Iceland. At that time the electricity system of the area was not connected to the national grid. This large increase in the stations capacity was to be achieved by building a higher dam, that would then flood some of the valley above and affect the salmon fishing in the river. This scheme met with fierce opposition from the local people mainly, but also from environmentalists in general. The plan for the dam was eventually abandoned, although with new generating equipment it has now been possible to increase the capacity to about 20 MW electrical.

Exploration of the Krafla geothermal area was initiated in 1970 and carried out according to the Orkustofnun "program for the exploration of high-temperature areas in Iceland" (Björnsson 1970 and Stefánsson 1981). In 1971 the first progress report was published by Orkustofnun (Saemundsson, K. (ed.) 1971). This work was not done with any specific utilization in mind, but in 1972 a preliminary project report was published by Orkustofnun (Ragnars & Matthíasson 1972) on the feasibility of construction a 8 MW, 12 MW or 16 MW geothermal electric power plant in Námafjall or Krafla. The results were considered sufficiently encouraging to warrant further study and in 1973 a feasibility report was published by Orkustofnun (Ragnars et al. 1973) on the above sized stations and also a 55 MW station. The station was to consist of a single-pressure condensing turbine operating at 4 bar-a saturated steam. The experience already gained in Námafjall was used as the basis for the report such that the reservoir temperature was assumed 260°C. This meant that about 4-4-5-15 boreholes were required respectively. It was concluded that the price of electricity from these stations would be 11.0, 8.4, 7.5 & 4.5 m$/kWh respectively - the economy of scale was clear. The estimated production costs of the electricity was considered comparable to those expected from the next hydro-power stations to be built in Iceland. What these

prices were was however unclear. The 1973 report was really an up-date of the 1972 preliminary report with a 55 MW power station added. It is difficult to up-date the estimated electricity cost to 1980, but assuming 10% annual dollar inflation the costs are in the range 10-20 m$/kWh, which is similar or lower than estimated for new and large hydro-stations in Iceland in 1980.

By late 1973 it was considered that the electricity supply situation in north-east Iceland would shortly become critical because now the Laxá dam scheme had been abandoned. The preliminary and tentative plans for a geothermal electric power station in the Lake Mývatn region, namely Námafjall or Krafla, were suddenly the subject of great interest. In 1974 the parliament (Althing) debated and authorized the construction of a 55 MW power plant to be located in Námafjall or Krafla. An ad-hoc committee was formed by the Ministry for Industry (and energy), known as the Krafla Project Executive Committee. It was to be responsible for the construction of the power plant only, while the State Geothermal Steam Supply at Orkustofnun was to develop the geothermal field and produce/deliver the geothermal steam to the plant. The State Electric Power Works were given the responsibility of building the 132 kV transmission line to the town of Akureyri. All the 3 organizations involved were requested to carry out their task as quickly as possible, because of the imminent shortage of electricity. Formally, all the organizations reported to the Ministry for Industry. Iceland was to have its first major geothermal electric power plant. The events that followed developed differently than imagined and the Krafla Geothermal Power Plant became the most controversial issue in Iceland for years. It is perhaps relevant to reiterate that one of the purposes of the present paper is to report on the experience of Iceland in geothermal electric power. This is not an easy task when it comes to the subject of Krafla. In the follwing an attempt will however be made to report as objectively as possible.

Geothermal Area

The State Geothermal Steam Supply was responsible for the development of the steam field. The first issue that had to be resolved was to decide where to build the power plant. The Námafjall area was already well

known, but no drilling had yet been done in Krafla. The State Drilling Contractors at Orkustofnun were contracted to drill two (~1200 m deep) exploration boreholes in 1974 and the Geothermal Division of Orkustofnun was engaged to carry out all the geoscientific work. In early 1975 the Geothermal Division reported (Saemundsson et al. 1975) on the exploration drilling and concluded, that the Krafla geothermal area would probably be able to produce the required amount of steam (estimated as 470 tonnes/hour of steam from 650 kg/s of 260°C reservoir water) for a 50-60 MW power station. Because the Krafla geothermal area is much larger than the Námafjall area (about 4 times greater) the former was favoured as the site for the power plant. It was also the view of the Environmental Protection Board (Náttúruverndarráð) of Iceland that the Krafla site would be a better choice. When it became known in early February 1975 that the Krafla Project Executive Committee had decided to buy two 30 MW steam turbines, it was argued by Orkustofnun that it was both "unusual and risky" to start building the power house concurrent to production drilling in the area (Orkustofnun 1978). The view presented was that the power house should not be built until production drilling had verified the expected production capacity of the field. Three boreholes (1300-2000 m deep) were drilled in the summar of 1975, six (1300-2200 m deep) in 1976, one (~2200 m deep) in 1978 and three (2000-2100 m deep) in 1980. The drilling history and the exploration of the Krafla geothermal field developed in such a way that reporting it requires more space than is available in the present paper. Stefánsson (1981) has made an excellent report of the status of the project in late 1978.

The geothermal system in Krafla consists of two separate zones. The upper zone extends down to about 1100 m depth being a water-dominated system with a mean temperature of 205°C. The lower zone ranges from 1100-1300 m depth to at least 2200 m, which is the depth of the deepest borehole. This lower zone is considered to be in a state of boiling with a mixture of steam, water and gases (mainly CO_2) in the formation. The temperature of the lower zone ranges from 300°C to 350°C and it is found that both temperature and pressure are close to saturation. There is evidence to show that the two zones are connected by an upflow channel near the centre of geothermal manifestations at the surface. The production characteristics of the boreholes are very different because they receive fluids from either one or both of the zones. The zones have

different reservoir properties, superimposed on which are the influences of magmatic activity in the area. The upper zone is similar to other high-temperature fields known in Iceland while the lower zone is characterized by a high gas content and a high enthalpy of the fluids discharged. Due to the relatively low temperature of the upper zone and a problem of calcium carbonate ($CaCO_3$) deposition associated with the water, this zone is now cased off when drilling new boreholes. Deposition problems have also been associated with fluids from the lower zone, giving rise to deposits consisting mainly of iron compounds (FeS, FeS_2 and Fe_3O_4) and silica (SiO_2). Some of the wells have to be worked over and cleaned by drilling about once a year. The deposition problem associated with the lower zone is believed to be at least partly due to magmatic influence.

Volcanic Activity

In December 1975 a volcanic eruption occured in Leirhnjúkur about 2 km from the Krafla Power Plant (Figure 4). This volcanic eruption was the beginning of a rifting episode in the fissure swarm intersecting the Krafla caldera (Björnsson et al. 1977). During the last 5 years this volcanic activity has continued with 12 rifting episodes, 6 of which have resulted in volcanic eruptions. The magmatic activity has influenced the production characteristics of the Krafla geothermal area and given rise to several difficulties experienced in its utilization. Volcanic activity is still going on in the Krafla area, affecting the boreholes and reservoir properties in both the Krafla and Námafjall geothermal fields.

Power Station

The power station in Krafla was built by the Krafla Project Executive Committee. In late 1974 the committee engaged two engineering consulting firms to undertake the design, purchasing of equipment and supervising the construction of the power plant. These were Thoroddsen & Partners in Reykjavík and Rogers Engineering in San Francisco who in April 1975 presented as a joint venture a preliminary design report (Krafla Project Executive Committee 1975). Prior to that the committee had entered into negotiations with Mitsubishi Heavy Industries in Japan

to buy two complete 30 MW turbine-generator units. Most of the mechanical engineering design of the power plant was done by Mitsubishi while the consulting firms designed the power house building and auxiliary equipment. Elíasson et al. (1980) have reported in detail about the Krafla Power Station.

The power station was to have two 30 MW-electrical turbines utilizing steam flashed from geothermal water at two different pressures. It was stated that a double flash system reduces the hot water requirement from the boreholes by approximately 20%, as compared to a single flash system, and at the same time gives more flexibility of operation for possible future changes in steam conditions. The design of the power plant was based on the assumption that the borehole water would have an average temperature of 270°C. In the autumn of 1977 the first 30 MW unit was completed and tested and in February 1978 the power plant was commissioned on part load. Great difficulties were experienced in producing sufficient steam for the power plant, delaying its commission by one year. The second 30 MW unit has never been installed and is now in storage for future use. Because of the great uncertainty in the ability of the Krafla Power Station to be on-line producing electric power for the north-east region of Iceland, the construction of a 132 kV transmission line from the south of Iceland - where most of the hydro-power is generated - was hastened. At the same time the transmission line to Akureyri and onwards had been or was being completed. It meant that the north-east would be connected to the national grid and one of the main reasons for needing the Krafla Power Station evaporated. The new electricity transmission system was commissioned in January 1977 and the Krafla project had entered a new phase.

The flow diagram for one 30 MW unit is shown in Figure 6. The steam-water flow from the boreholes is piped to the separator building which contains all high-pressure and low-pressure separators for one unit. The high-pressure separators operate at 8.7 bar-a pressure. The high-pressure steam is manifolded from the separators into a single pipeline which brings the steam to the power station. A second flash steam separator is used to boil off and separate all the water from the high-pressure separator in a single separator at a considerably lower pressure or 2.2 bar-a. The primary steam enters the turbine at 7.2 bar-a pressure

and the secondary steam enters at 2.0 bar-a pressure between the second and third stages. The turbine is a single-cylinder, double-flow, dual-admission unit with 5 stages. It has a underlying direct contact jet condenser. The vacuum of the condenser is at 0.12 bar-a. The high-pressure geothermal steam contains 1.5-1.7% of non-condensable gases at the present time. It is extracted with steam ejectors. There have been some difficulties with the gas extraction system because at times the amount of non-condensables has been excessive. The combined cooling water and condensate is pumped out to a crossflow forced draft cooling tower by a hot-well pump. The cooled water from the cooling tower basin is recycled to condense the steam from the turbine exhaust. Experience has shown that the pH-value of the cooling water decreases to very low values if not adjusted with chemicals. It is normal procedure now to add soda ash (Na_2CO_3) to the cooling water to keep the pH-value above 5.

Steam Production

In the development of the Krafla geothermal electric power project, the main constraint has always been the great difficulty experienced in producing the steam. This was the task of the State Geothermal Steam Supply at Orkustofnun. The main cause of this difficulty was the limited knowledge of the Krafla high-temperature area when the project was initiated, which contributed to the lack of success in drilling. Although it is now widely accepted that more time should have been given to production drilling and discharge measurements, before the power station was constructed, the view at the time of critical decision marking in 1974-1975, was that the Krafla field would be able to produce enough steam. The success achieved in Námafjall in the preceding years was probably the main source of this optimism. A factor of importance in this matter must also be the great haste that was called for in the overall planning of the project. Orkustofnun is mainly a research organization with an infrastructure reflecting that purpose. It could be argued that the manpower and project oriented resources required in the Krafla project were not readily available.

In the middle of 1975 Orkustofnun (the State Geothermal Steam Supply) engaged the engineering consulting firms of Thoroddsen & Partners and

Virkir Consulting Group, in Reykjavík, to undertake preliminary design, design, preparation of contract documents, bidding, final design and supervision of construction of the steam supply system (pipelines, separators etc.) in Krafla. Their preliminary design report was presented several months later in November (Orkustofnun 1975). The disposal of waste fluids was also dealt with in that report. During the 1975 drilling season there occured a blow-out while drilling borehole 4 that could not be controlled. Borehole 5 was not drilled to full depth because of that blow-out. And in December 1975 there was a volcanic eruption in the Leirhnjúkur part of the Krafla high-temperature area. In the following year the organizations involved in the Krafla project discussed the abandonment of the project, for the time being, on account of this "force majeur" situation. It was however not to be and the Krafla project continued.

The high- and low-pressure steam are piped to the power station about 500 m from the separators station. At the end of 1980 eight boreholes of the 15 drilled were producing steam (Table 4). Most of these are located within 500 m of the separators station spaced 100-300 m apart. One producing borehole, 14, is located in a new section of the geothermal area about 1000 m distance from the separators. It is also the best producer and in future it is hoped that this section of the field will be capable of producing the additional steam needed. The total production of the field in late 1980 was 168 kg/s from 11 boreholes of which 88 kg/s came from the 8 that were connected with pipelines. The 4 boreholes not producing anything were either damaged or not completed. The enthalpy of the steam-water mixture discharged from the 8 boreholes utilized is in the range 1100-2900 kJ/kg. These boreholes produce in total 53 kg/s of high-pressure steam (8.7 bar-a in separator) of which 10 kg/s are from 9 and 17 kg/s from 14 such that 1/2 the steam comes from two boreholes. In total about 130 kg/s of high-pressure steam are required for two 30 MW turbine-generator units. It is hoped to drill 3 boreholes every year for the next 5 years, in all 15 boreholes. If these new boreholes produce about 10 kg/s of high-pressure steam, which seems reasonable in light of borehole 14 drilled in the new section of the field, the Krafla Power Station might be on full load by 1985.

It was stated above that the actual (measured) amount of non-condensables

in the high-pressure steam entering the turbine, is usually in the range 1.5-1.7% by weight. These percentages do not reflect the extreme values measured in the steam from individual wells, because some of them are indeed high. To illustrate the composition of the non-condensables in Krafla it was decided to calculate the gas concentration in the steam from the best producers, K-9 and K-14. Table 8 shows the estimated concentration of non-condensables when the steam-water mixture from these two boreholes is allowed to flash at 175°C which corresponds roughly to the separator pressure of 8.7 bar-a. The gas content is about 1.9% and 1.2% which is an order of magnitude greater than in Námafjall and Svartsengi.

Turbine Inspection

The main materials of construction selected for the Krafla power station were the following: Carbon steel for steam pipelines and separators, stainless steels for turbine nozzles, 12-13% chrome stainless steel for turbine blades and 2-3% nickel steel for the rotor. Austenitic stainless steel was used in most metal components in the condensate cooling system and aluminium or stainless steel for majority of structures in atmospheric exposures (Elíasson et al. 1980).

By July 1979 the turbine-generator unit of the Krafla station had only been operated for about 300 days. At that time the station was closed down for a detailed inspection of the steam turbine and associated equipment. Thórhallsson et al. (1979) carried out and reported this inspection, which concerned the corrosion, erosion and deposition problems experienced in the operation of the plant. The 1st operating period was 28 July 1977 to 19 August 1977 (22 days), the 2nd 4 February 1978 to 11 July 1978 (157 days) and the 3rd 30 January 1979 to 4 July 1979 (125 days). In every one of these periods there had been experienced difficulties in the operation of the main control valves of the turbine and deposited material had been found in the steam strainers and various valves. These difficulties became greater in each operating period.

It was discovered during the inspection that considerable erosion and corrosion had occured. The main problem was erosion in the steam turbine and associated equipment. The cause of this was considered to be mill-

scale (and subsequently particulate corrosion products formed during shut-down) from the steam supply system. A contributing factor may also have been aggressive corrosion gases from borehole 12 that produced dry superheated steam. This steam was for some time piped directly into the high-pressure steam line, causing great difficulties because erosion-corrosion occured at the point of entry. The well-head of borehole 12 had to be replaced after only 6 months due to excessive corrosion. After the inspection in 1979 the station has operated on and off at a load of 6-12 MW-electric.

Concluding Remarks

The Krafla Power Station was commissioned in early 1978. At the end of that year there were made great organizational changes in the whole project. The Krafla Project Executive Committee was disbanded and the State Electric Power Works (Rarik) were given the responsibility for the whole project. The State Geothermal Steam Supply at Orkustofnun was similarly relieved from producing the steam. Now the State Electric Power Works operate the plant and contract the State Drilling Contractors at Orkustofnun to do the drilling and the Geothermal Division of Orkustofnun to carry out the geoscientific work. This new arrangement, where one company is responsible for the whole project, has proved satisfactory.

It was reported by Stefánsson (1981) that by the end of 1978 the total cost of the Krafla project had reached 55 million U.S. dollars and the annual capital cost was estimated to be about 5 million U.S. dollars. Assuming 10% dollar inflation and adding the cost of drilling boreholes 13-15 (at about 1 million U.S. dollars each), the total cost by the end of 1980 must have been close to 80 million U.S. dollars. On the assumption that 3 boreholes will be drilled each year until 1985 (see above) the total cost by then (in 1980 dollars) may amount to 120 million U.S. dollars or more when both units (2x30 MW) have been installed, resulting in 2000 $/kW. This value is very tentative and only a rough estimate.

SVARTSENGI

Regional Heating

In the last decade the percentage of Icelanders enjoying geothermal district heating increased from about 40% to 70% of which 5% (of total population) are now supplied with hot water from Svartsengi (Gudmundsson 1976, Gudmundsson & Pálmason 1981). It was in 1969 that the town of Grindavík in south-west Iceland requested Orkustofnun to explore for geothermal energy in its neighbourhood. Following geological work and resistivity measurements a potential geothermal area was identified about 5 km north of the town, which subsequently became known as Svartsengi. In 1971-1972 two boreholes (240 m and 400 m) were drilled and it was discovered that Svartsengi was a high-temperature area and that the hot water produced was saline with a composition about 2/3 that of seawater. The two boreholes were good producers, discharging in total about 130 kg/s of about 235°C brine.

Although the exploration and drilling in Svartsengi had been successful, the problem was that the high-temperature brine could not be used directly for district heating purposes. At about the same time it was being considered to use flashed high-temperature geothermal waters (non-saline) for district heating in Námafjall (Reykjahlíd village) and Hveragerdi. These new systems were taken in use in 1971 in Námafjall and 1973 in Hveragerdi, the latter one replacing a much older system that was based on shallow boreholes within the town. Both of these systems experienced difficulties because of silica deposition in the transmission lines and distribution networks (Thórhallsson et al. 1975). Subsequently these problems were solved by not using the flashed water but instead the steam, which was injected into cold fresh water and then degassed in a flash-tank at atmospheric conditions. Not very energy efficient, but satisfactory for the small utilization involved.

It was clear that a novel method had to be developed if the high-temperature brine in Svartsengi was to be used for geothermal district heating. In early 1973 Orkustofnun published a preliminary feasibility report (Ragnars & Björnsson 1973) about district heating from Svartsengi, not only for the town of Grindavík, but all the main towns and villages in

the Sudurnes region. It was proposed to construct a special heat exchange plant where fresh cold water was to be heated by using the steam-brine mixture produced in Svartsengi. The economic analysis showed that such a system could provide geothermal district heating at a cost of about 1/3 that of individual oil-fired heating. It was decided to test several heat exchange arrengements and for that purpose a pilot-plant was built near the two boreholes (2 and 3) that had been drilled in 1971-1972. The pilot-plant was started up in early 1974 and operated until 1975 during which time several process arrangements were tested. These were later the basis for design of the present power plant in Svartsengi. Arnórsson et al. (1975) have reported some of the early results. Resistivity measurements were continued in 1973 and the two boreholes were tested for flowrate and chemical characteristics. Two deep production boreholes (4 and 5) were drilled by Orkustofnun in 1974 to depths of 1600-1700 m. These proved equally successful producing more than 80 kg/s each of the 235°C steam-brine mixture. As the Svartsengi project was developing from exploration to pilot-plant studies, the price of oil suddenly quadrupled. This activated the support needed to develop the project further. At the turn of 1974/1975 a consortium was formed to exploit the Svartsengi high-temperature area for district heating in the Sudurnes region, which consists of the seven separate towns and villages on the Reykjanes peninsula. The consortium became known as Sudurnes Regional Heating and is owned 60% by the local communities and 40% by the state. The reason for the participation of the state stems from the fact that by Keflavík there is an international airport and a NATO military base. The thermal power required for district heating in the seven communities was estimated as about 40 MW in 1976. This refers to the thermal power consumed above 35-40°C. The total capital cost of a power plant with this capacity was estimated about 20 million U.S. dollars in 1976. The thermal power requirement of the international airport and military base was estimated slightly higher or close to 45 MW.

In late 1975 the Sudurnes Regional Heating consortium engaged two engineering consulting firms to be responsible for all the design work and purchasing of equipment as well as supervising the construction of the power plant and pipelines etc. The firms were VGK Consulting Engineers (Verkfraedistofa Gudmundar & Kristjáns) and Fjarhitun Consulting Engineers, both in Reykjavík. The power plant was a joint venture of VGK and

Fjarhitun, the former being responsible for mechanical engineering and overall planning, while the latter looked after the civil engineering. Another agreement was made between Sudurnes Regional Heating and Fjarhitun regarding the more traditional hot water transmission lines and distribution networks and the fresh water gathering system. These main consultants then engaged other specialized consulting engineers and architects. The Sudurnes Regional Heating made an agreement with the Geothermal Division of Orkustofnun to carry out further geoscientific work and to act as consultants in the power plant design. The three consultants have now worked for about 5 years in close cooperation to aid the consortium in making the novel power plant in Svartsengi a most successful project. The State Drilling Contractors at Orkustofnun have drilled all the boreholes in Svartsengi.

Geothermal Field

The Svartsengi high-temperature area is on the Reykjanes peninsula as shown on Figures 1 and 5. It consists of two fields one of which is named Svartsengi and the other Eldvörp. No drilling has yet been done in the latter, which is located about 5 km to the west of the Svartsengi production field. The Reykjanes high-temperature area is at the tip of the Reykjanes peninsula, about 15 km from Svartsengi, while the main Krísuvík field is located about 20 km to the east of Svartsengi. All these high-temperature geothermal areas are on the Reykjanes peninsula seismic belt which is inside the active volcanic zone laying from the south-west of Iceland to the north-east. The geothermal field in Svartsengi has been investigated in detail by Orkustofnun and some of this work has been published in English (Arnórsson et al. 1978, Kjaran et al. 1979, Thórhallsson 1979 and Georgsson 1981). Recently Kjaran et al. (1980) reported extensively about the reservoir engineering studies that have been carried out in Svartsengi from the start of exploitation. The following account of the geothermal field in Svartsengi is based on their report.

The geothermal water produced in Svartsengi is believed to originate partly as rainfall in the highland of the Reykjanes peninsula. There the water percolates downwards to about 3 km depth and then flows westwards along the so called earthquake zone. This earthquake zone is a

3 km wide belt extending from Lake Kleifarvatn (the Krísuvík high-temperature area is there) seawards along the peninsula within which almost all earthquake foci in Reykjanes occur. The earthquakes keep the axis of flow open. Mixing with seawater occurs to the extent that the geothermal fluid is 2/3 seawater at Svartsengi. It seems possible that the high-temperature areas in Reykjanes are formed where surface fault swarms intersect the earthquake zone. The increased permeability of the fault areas makes convective heat transfer to the upper layers possible.

Geological observations show that at Svartsengi the main geothermal reservoir is capped by an impermeable layer at about 600 m depth. Below this depth the reservoir rock is very permeable consisting of basalt layers with dolerite intrusions. The hydrological model of the geothermal area assumes that the upward flow of hot water reaches the caprock, cools to some extent and flows downwards again mixing again with the inflow. Thus a convection cell is formed which results in an even temperature distribution in the geothermal reservoir (240°C). Where the caprock is fractured the hot water boils on the way up and steam is released to the surface. There are no thermal springs at Svartsengi, but the natural effluent reaches the surface lavas and is carried away with the groundwater flow. Well testing at Svartsengi has shown that the geothermal area has a permeability of 1 darcy, which is one of the highest values observed in any geothermal area. In spite of this production causes a large pressure drop which is due to the fact that the geothermal reservoir is small, the most porous area being only about 2 km^2 in area with impermeable sides in three directions. It is predicted that the pressure decline will considerably limit long-term exploitation of the field.

On the basis of a yearly district heating utilization of 4000 hours, a water level drawdown of 200 m could be expected in 25 years while on the basis of additional 8 MW electricity production at 6000 hours per year a drawdown of 250 m could be expected in the same period. Because of the high permeability the steam-brine output of boreholes in Svartsengi is entirely dependant on the width of the hole and reservoir pressure. For this reason amongst others wider boreholes than usual have recently been drilled. Calcium carbonate precipitation occurs in the boreholes at the depth of boiling which decreases with the lowering of reservoir pressure,

and determines for example the acceptable pressure reduction in the area.

According to heat loss calculations of the geothermal area it seems likely that on average 230-560 kg/s may be extracted if waste water is reinjected into the system. Calculations on the pressure reduction in the area, based on a drawdown of 200 m, suggest that it will be possible to maintain production for the required district heating and the generation of 8 MW of electricity for 4000 hours per year until the end of the century. However in this case the reinjection of the waste water is not taken into account.

Power Plant

The novel heat exchange process used in the Svartsengi power plant has been described by Thórhallsson (1979). The power plant is designed for heating fresh water for district heating by using geothermal steam flashed from the steam-brine mixture produced by the boreholes. The fresh water is pumped from shallow wells about 4 km away from the plant. High fouling rates of heat exchanger surfaces dictated that only flash steam be used for the heat exchange process (Gudmundsson & Bott 1979). The pilot-plant studies demonstrated, moreover, that the flash steam could be used directly (Arnórsson et al. 1975) to heat the fresh water by injection. Subsequent tests showed, however, that because of the high carbon dioxide (CO_2) content of the steam, the deaeration was much easier to accomplish if the high-pressure steam was condensed in a surface heat exchanger, rather than being directly injected. This arrangement also facilitated the inclusion of a back-pressure steam turbine in the flow-stream.

The flow diagram of the power plant is shown in Figure 7 , illustrating the main equipment and associated flowrates, temperatures and pressures. There are 4 parallel flow streams in power plant I, like the one illustrated in the figure. Two of these are as shown, while two have additional heat exchangers (inter-coolers) that can cool the deaerated water from about 100°C to 85°C to be pumped directly to Grindavík. About 15% of the population served by Sudurnes Regional Heating (excluding international airport and military base) lives in Grindavík, which is 5 km south of Svartsengi, while the bulk of the Sudurnes population live in

and around the town of Keflavík 12-15 km away to the north-west. The international airport is also located by Keflavík. Because of the low population density in the coastal communities and the relatively long distances involved, it was decided to use a single-pipe distribution system but with a two-pipe system for the airport area itself. The hot water is pumped from the power plant at ~85°C to Grindavík but at ~125°C to Keflavík where it will be mixed with ~55°C return water delivered at about 95°C to the international airport. This arrangement reduces the fresh water requirements by about 50%. The hot water supply temperature to customers in Keflavík and neighbouring towns will be about 80°C. Tap-water requirements are met directly from the system thus dictating the temperature of the delivered water. The spent water is discharged to the sewer system at 30-40°C.

In the design of the power plant the silica chemistry of the geothermal brine dictated the operating pressure selected for the high-pressure steam separators. The geothermal brine in the reservoir is saturated with silica according to the solubility of quartz, but when it flashes in the borehole, pipelines and separators, it is however amorphous silica (opal) that determines the onset of deposition (Gudmundsson & Bott 1977). In the Svartsengi brine opal saturation is reached when it has flashed and cooled by about 100°C from 240°C to 140°C. The high-pressure separators are however operated at a pressure (5.4 bar-a) corresponding to a saturation temperature of 155°C to provide an acceptable margin of safety.

The selected separation pressure determines the temperature and flowrates within the system. The flow is balanced to use all the high-pressure and low-pressure steam generated, based on a reservoir temperature of 240°C. The power plant design is based on a steam-brine production of 60 kg/s from each borehole, an output which is split between two flow-streams. Power plant I has four flow-streams, as already stated, such that two boreholes are required on-stream at any one time. Each flow-stream produces sufficient hot water to satisfy a 12.5 MW thermal load at the consumer, the rated capacity of the power plant therefore being 50 MW-thermal.

The geothermal steam-brine mixture is piped in two-phase flow from the wells to a flash plant located by the power-house. See Figure 7. Two

centrifugal steam separators in series produce the high-pressure (5.4 bar-a) and low-pressure (0.25-0.39 bar-a) steam. The water level in the high-pressure separator is controlled and the spent brine discharged from the barometric leg of the low-pressure separator is presently disposed of into a large pond by the power plant (see later). The high-pressure steam is used for the generation of electricity in a back-pressure turbine before being condensed in a plate heat exchange. The low-pressure steam is piped to a direct contact condenser where it preheats the fresh cold water from 5°C to 65°C and removes 90% of the dissolved gases from the fresh water. This water is pumped (in two of the flow-streams) to the turbine condenser mentioned above. In the other two flow-streams there is the possibility of pumping the water first through inter-coolers as mentioned above to produce, on the other side, 85°C water for Grindavík. In the turbine condensers the water is heated to 105-110°C before it enters the atmospheric deaerator. At this point the hot water is heated further by high-pressure steam in a plate heat exchanger to 125°C for pumping to Keflavík, or cooled to 85°C in the inter-cooler. The degree of instrumentation allows the power plant in Svartsengi to be run by one operator per shift.

The equipment in the power plant is mostly of standard manufacture and selected with the service conditions in mind. The flash plant and deaerating equipment are however of special design. Mild steel is used in all the steam-brine pipelines and separators while stainless steel is used in the pipes for the heated fresh water before deaeration and for the steam condensate. The plate heat exchangers are mainly made of stainless steel but titanium was used in some of the early units. The performance of all the materials has been satisfactory. There has been some silica scaling in the high-pressure separators (0-2 mm/year) and low-pressure separators (1-3 mm/year) but it has not caused any difficulties in the operation of the plant. Rapid silica deposition occurs, however, in the surface drains from the low-pressure separators, as would be expected, because by then the silica concentration is 125% above the solubility limit of amorphous silica (Gudmundsson 1978).

The production of district heating water started in November 1976 in Svartsengi when a temporary heat-exchange plant was put into oparation. It was similar to the simple systems described above that are now used

in Hveragerdi and Námafjall. The steam-brine mixture from borehole 4 was separated at 4.1-4.2 bar-a pressure the brine being discharged to the disposal pond through a concrete silencer. The steam at about 145°C was injected into warm water at about 15°C heating it well above 100°C. The water was then flashed at ambient conditions to remove the dissolved oxygen in the fresh water and carbon dioxide (mainly) from the condensed steam. This degassing took place in an open concrete cylinder from which the near 100°C water was pumped through a heat exchanger that heated the fresh water from about 5°C to the stated 15°C. The district heating water was now about 95°C and could be pumped to the town of Grindavík only. Before leaving the temporary station the pH of the water was increased to a value of ~9 by dosing with a solution of caustic soda. If too much caustic was added there deposited some magnesium silicate (Kristmannsdóttir 1980). This temporary station operated until August 1979. The first flow-stream of power plant I was commissioned in December 1977. There have been traces of magnesium silicate deposition from the hot water produced in the power plant but the problem can be controlled by careful operation of the deaeration units.

The total capital cost of the Sudurnes Regional Heating system, from boreholes to house-connections, has not yet been added up. It was stated above that in 1976 the capital cost was estimated 20 million U.S. dollars. A rough estimate of the capital cost of power plant I and all the associated boreholes and hot water distribution network, amounted to about 35 million U.S. dollars in 1980. This amount should be compared to the 1976 estimate. Power plant II is presently under construction and it is estimated to add another 15 million U.S. dollars to the total capital cost. These cost estimates are only tentative.

Power plant II is being constructed for the purpose of supplying district heating water to the Keflavík International Airport and NATO Military Base. Initially it is to have 2 - 3 flow-streams of a new design, each with a rated thermal capacity of 25 MW. The present thermal requirements of the international airport area is estimated as 45 MW. In this new design the low-pressure separator, direct contact condenser (or pre-heater) and deaerator are to be combined in one column. Successful tests were carried out, using equipment in power plant I, indicating that this new design would perform to the same standard as the older units. It is hoped that

capital cost savings can be made in the construction of the new column. The low-pressure steam goes to a heater/deaerator which is operated under vacuum and then heated further in a plate heat-exchanger using back-pressure steam from the 6 MW turbine (see later) and also some additional steam directly. Two flow-streams are due to be completed in 1981 and the power house has space for four flow-streams in total. The present pipeline to Keflavík is wide enough to carry all the hot water needed in the foreseeable future. It is not known how the thermal market at the international airport will grow in the years to come, but projections have been made for the general heating market in the rest of the Sudurnes region. Assuming no growth at the airport it is estimated that the thermal market will be 75 MW in 1981, 85 MW in 1985, 105 MW in 1990, 115 MW in 1995 and 135 MW by the year 2000.

Turbines

There are two AEG-Kanis 1 MW back-pressure steam turbines in power plant I of Sudurnes Regional Heating. Table 6 shows their main technical specifications. These are built as process or pump drives to be operated at double their present speed of about 4500 rpm. Björnsson (1978) of VGK Consulting Engineers has presented details about these turbines. The amount of steam expanding through the turbine in Figure 7 is sufficient to generate about 0.6 MW of electricity. The high-pressure steam associated with two flow-streams in power plant I is used for each turbine-generator. Thórhallsson et al. (1980) have reported the first year experience gained in operating one of these units. The first turbine was commissioned in late April in 1978. In December the same year it became clear that the labyrinth seal was not performing as it should and the safety valves (governor valve spindle in gland) were difficult to move. The venting arrangement for the seal was found to be faulty and parts of the machine had to be repaired. The second turbine-generator unit was commissioned in 1979. Both units have operated on and off since that time. The main purpose of these turbines is to provide the power plant with electricity for pumps and other equipment. Table 7 shows the amount generated. The inlet nozzles and stationary blades are made from 13% Cr-steel while the turbine blades are 13% Cr, 1.1% Mo and 1% Ni-steel. When inspected after one year of operation the first unit showed no signs of corrosion. The one difficulty to arise has been rapid salt deposition

during a short time when a high-pressure separator was overloaded. The later designs of separators have an internal steam pipe while the older ones have the steam outlet at the top. Both types have wire-mesh mist eliminators.

In the last few years there has not been as much water available to the various hydro-power stations in Iceland as in the past. New electricity intensive industry (ferrosilicone) was started and the Krafla Power Station did not produce the power expected. This has caused difficulties in meeting the electricity demand in the most recent years. After 1981 this situation will have improved because a large hydro-power station under construction by Landsvirkjun (National Power Company) will be on-line. This shortage of electricity caused the Sudurnes Regional Heating consortium to bring forward the installation of a 6 MW geothermal electric power station in Svartsengi. Great haste was called for and in December 1980 the unit was put into operation. See Table 6 for main specifications. The turbine-generator unit is package-type made by Fuji Electric in Japan. Three governor valves are provided to ensure better performance at partial load expected in summer time. Pure steam from a steam converter is used as gland sealing steam to protect the gland packing from corrosion. The nozzles, stationary blades and moving blades are all made from 13% Cr-steel. The unit is located in power plant II and will in future be operated as an intergral part of the new plant design.

Steam Production

At the end of 1980 ten geothermal boreholes had been drilled in Svartsengi, two each by Grindavík town and Orkustofnun, and six by Sudurnes Regional Heating. About 25 hectares of land, for the purpose of constructing buildings and pipelines etc., were owned by the regional heating consortium in late 1980. Also, the consortium owns the right to all geothermal energy in an area of 400 hectares. The construction land and the energy resource were bought in 1977 at a total price of about 300,000 U.S. dollars. This price was arrived at by arbitration. As a general rule in Iceland, the geothermal energy is owned by the landowner. Several moves have been made to give the state all rights to high-temperature geothermal energy, but these have not been successful yet. However, as it happens, most of

the land where high-temperature geothermal areas are located, is either state or community owned.

The boreholes in Svartsengi are of three basic designs: a) 2, 3 and 10 are shallow 239 m, 402 m and 424 m closely spaced 35-105 m, b) 4, 5 and 6 are deep 1713 m, 1579 m and 1734 m with 9 5/8" production casing and c) 7, 8, 9 and 11 are deep 1438 m, 1603 m, 994 m and 1141 m with 13 3/8" production casing. Boreholes 2 and 3 have 8 5/8" production casing while 10 has 13 3/8". Alle boreholes have slotted liners except 7 which is "barefoot". Boreholes 5-11 are spaced 200-250 m apart being 300 m nearest to 2, 3 and 10. The boreholes drilled by Sudurnes Regional Heating were completed 1978 and 1979 one each year, but four in 1980. The design output of the boreholes with 9 5/8" production casing is 60 kg/s (240°C steam-brine mixture) but the 13 3/8" boreholes have 120 kg/s as nominal capacity.

Flowrate (and enthalpy) measurements have been done on all the Svartsengi boreholes. Figure 8 shows some of the results. Borehole S-4, being 9 5/8", produces 60-80 kg/s at 10-15 bar-a well-head pressure, while S-8 and S-11, being 13 3/8", produce 120-180 kg/s. Well S-10, shallow 13 3/8", is capable of similar production as the other wide holes. Borehole S-7 which is "barefoot" has typical 13 3/8" characteristics but has not yet been tested at higher flowrates. It should be noted that boreholes of similar design (see above) have comparable production characteristics. The wide boreholes in Svartsengi are probably among the best producers in the world. The enthalpy of the steam-brine mixture in all the boreholes corresponds to water at 235-240°C. It has remained constant since the start of production as has the fluid composition.

Borehole 4 was used for the temporary heat exchange plant that started operation in late 1976. The borehole was damaged in 1979 due to casing failure and is no longer useful as a production hole. The failure accured at welded joints in the liner at about 500 m with the result that the part of it below that depth dropped 40-50 m down the hole. There was also an unexplained hole in the casing at shallow depth which was repaired. Also in 1979, there was discovered at shallow depth a casing

collapse in borehole 5, probably as a result of poor cementing. This collapse was repaired. There were therefore 9 producing boreholes in Svartsengi at the end of 1980. Borehole designated as 1 is not geothermal and was drilled outside the field for fresh water used in the early drilling operations. In boreholes (4), 5 and 6 there has been experienced calcium carbonate ($CaCO_3$) deposition at the depth where flashing starts. These deposits are formed in the depth range 350-450 m and boreholes (4), 5 and 6 have to be cleaned every 7-8 months. This gives rise to extra wear and tear as evident in borehole 4. The deposits form a venturi-type throat that closes the borehole gradually at first, but then rather suddenly. For cleaning the borehole has to be "killed" by pumping cold water into it and then a small rotary drill-rig is used to drill out the deposit. This type of cleaning has been practiced for years in shallower and less powerful boreholes in Hveragerdi (Hengill high-temperature area) but without having to "kill" them. It is a two day operation to clean the boreholes in Svartsengi.

It was partly because of the calcium carbonate deposition problem that it was decided to drill wider boreholes and use 13 3/8" production casing instead of 9 5/8". It about doubles the cross-sectional area of flow such that cleaning would not be needed as frequently. These holes are not more expensive to drill, all it requires is a greater load on the drill bit because of the greater diameter. An added bonus in Svartsengi has been the large increase in output, which has about doubled. One reason for this success is the extremely high permeability of the reservoir (see above). The main flow resistance being in the borehole itself.

At the end of 1980 all the production boreholes had been connected to the power plant, wells 2, 3, 5, 6 and 10 to power plant I and wells 7, 8, 9, and 11 to power plant II. There is one high-pressure steam-brine separator for each borehole. By now the pipelines and separators have been inter-linked to provide for more flexibility in operation. In power plan II the pipes/separators are manifolded for even more flexibility. The separators in power plant II are larger than in the older plant, having nominal capacity of 80 kg/s (total flow) as compared to 60 kg/s.

The high-pressure steam produced in Svartsengi is of high quality. The separators operate with an efficiency of about 99.995% by weight such that brine carry-over is not a problem. The amount of non-condensable gases is similarily low, being typically 0.1-0.3% wt. Table 8 shows the estimated non-condensable content in high-pressure steam produced by borehole 6, when the steam-brine mixture is separated at about 155°C (5.4 bar-a), which correspond to normal operating conditions.

When completed the Sudurnes Regional Heating power plant in Svartsengi will be rated 150 MW of useful thermal power. It is therfore with comfort that the operators view the great individual production capacity of the boreholes drilled, because their total discharge rate is about double the estimated requirements. The geothermal reservoir itself is however considered limited, as discussed above, and there is considerable draw-down in the field. From 1976 to the end of 1980 the field had produced about 10 million tonnes of fluids, resulting in 55-60 m draw -down. The view is that there should not be excessive generation of electricity in the Svartsengi power plant in an effort not to exhaust the field too soon. The Svartsengi field has been monitored closely from the start of exploritation and there are now available continuous production and draw-down data. Kjaran et al. (1980) have modelled the field and predicted the pressure decline of the reservoir to the year 2000.

Drilling Cost

Borehole 8 is typical for the deep wells with 13 3/8" production casing. It was drilled to 1603 m in 1979 and costed about 560,000 U.S. dollars or 350 $/m, which should perhaps be compared to 365 $/m for borehole 11 drilled in Námafjall the same year, as shown Table 9. Drilling costs in Krafla are probably higher or 400-500 $/m in 1979 prices. Table 10 shows the total cost of drilling S-8 in Svartsengi. The main valves used on the boreholes in Svartsengi are W.K.M. 12" ANSI 600, which is a lower pressure class than used in Námafjall and Krafla.

ENVIRONMENTAL ASPECTS

The utilization of low-temperature geothermal energy for over 50 years in Iceland has not caused environmental problems. This is largely due to the favourable chemical composition of the thermal waters used. The low-temperature (60-130°C from the production fields) waters are of course primarily used for space heating and contain less than 500 mg/kg of dissolved soids in most instances. Geothermal waters used for space heating in Iceland are discharged into the sewer system when cooled down to 30-40°C. The production of hot water from the geothermal fields serving the Reykjavík District Heating Service has resulted in a draw-down of the water table and the disappearance of natural hot spring activity. The production capacity of these fields is approximately 10 times the estimated natural flow before drilling started. Gudmundsson (1980) has discussed the environmental aspects of geothermal energy production and utilization in Iceland.

The utilization of high-temperature geothermal areas in Iceland is both limited and recent in comparison to low-temperature areas. Drilling has been carried out in 7 of the high-temperature fields and presently 4 are being used for industrial, space heating and electricity generation purposes as shown in Table 4. In addition 2 fields are used for experimental and pilot plant purposes (see later). In the 12 years since the first major utilization of high-temperature gethermal energy started (excluding shallon boreholes inside the town of Hveragerdi) there have not been any significant environmental problems. There has however been expressed concern over topographical and visual matters. All major constructional undertakings in Iceland that are likely to affect the environment have to have the approval of the Environmental Protection Board. This applies to geothermal electric power projects as any other undertakings.

Aspects of environmental importance in each high-temperature geothermal area where there is electricity generation will now be described briefly. In Námafjall the boiling water from the concrete silencers

is discharged into a disposal pond where the water cools down before percolating into the highly fractured lava. It mixes probably with the ground water that flows towards Lake Mývatn, but no changes have yet been detected in the springs that feed the lake close to the geothermal field. In the years that the Námafjall high-temperature field has been in production, the disposal pond has not grown much in size. One of the reasons for this must be the low rate of silica deposition from the water. It is found in Iceland that silica deposition (polymerization) is much more rapid in saline geothermal waters (Arnórsson 1981).

In Krafla to the north of Námafjall, the water from the low-temperature separators is discharged into a small streams that runs down the valley to the south. Because some of the boreholes have a high enthalpy (large steam fraction), the amount of disposal water has not been as great as expected. Down the valley the small stream disappears into a lava field to join the ground water flow towards Lake Mývatn. The disposal stream and the ground water near the edge of the lava are closely monitoned. Both at Námafjall and Krafla there have been made measurements of heavy-metals and other chemical species that are potential pollutants. There are no indications that the disposal water causes environmental problems.

At Svartsengi in the south-west of Iceland, there is a disposal problem of a sort. The geothermal brine from the low-pressure separators (see above) is highly supersaturated with silica that polymerizes quickly to form colloidal silica that deposits in the disposal pond. The silica particles gradually seal the surface lava when percolating into the ground, with the result that the disposal pond increases relatively rapidly in size. In 1978 when 2 million tonnes of steam-brine mixture had been produced in the field, the surface area of the pond was 2700 m^2. The amount of flashed brine that is discharged into the pond is less than the steam-brine production from the field. When 5 million tonnes had been produced in 1979 the area of the pond was 4600 m^2 and in July 1980 when 8.5 million tonnes had been produced (in total from 1976) the area had grown to 7200 m^2. In future the plan is to reinject the waste brine

and condensate and presently work is underway to bring that about. Other work at Svartsengi of environmental importance, are detailed studies of the ground-water hydrology, land subsidence (levelling and gravity measurements) and seismicity. These are being monitored closely to find out if the production from the field will affect the environment. It is too early for any conclusions to be drawn. Similar studies are carried out in the Krafla-Námafjall region, but mainly to monitor the volcanic activity.

When reflecting on what main impact the development of high-temperature geothermal areas has had on the environment in Iceland, then surface disturbance must be ranked as important. The nature in Iceland is rather sensitive to disturbance and it can take a long time before a new balance is reached once some damage has been done. In this respect it should be kept in mind that there are "no" trees in Iceland such that any constructional work, roads, drill-sites, power-plant etc. are most visible.

CONCLUDING REMARKS

In the present paper the development and present status of geothermal electric power in Iceland have been expounded. It was shown that while there is great potential for generating electric power with geothermal steam, only about 6% of the 700 MW-electrical installed capacity uses that resource. The main "competitor" of geothermal electric power in Iceland is the relatively abundant and cheap hydro-power, while geothermal energy has no "rival" when it comes to thermal applications such as district heating. In the years to come the role of geothermal energy in electricity generation is not yet clear. After the Krafla experience there is limited confidence in Iceland in geothermal electric power. The main effort in this sphere in the next years will be to get Krafla into full production of which there are now indications after good drilling results in a new section of the geothermal area.

But the development of the power industry in general will continue and the next steps to be taken are presently heavily debated. Plans for large hydro-power stations have been made and several are reaching the stage of project design in preparation for bidding etc. The question that arises is wheather new geothermal electric power has any role to play before the year 2000. To answer that question Orkustofnun has engaged VGK Consulting Engineers in Reykjavík, to carry out a pre-feasibility study of a 50-60 MW geothermal electric power station to be located in one of the high-temperature fields in Hengill, south-west Iceland. The intention is to up-date earlier estimates taking into account the experience gained in Krafla (and Námafjall) and Svartsengi. When completed the results of the study will be compared to the cost of the next hydro-power schemes under consideration. As shown in the present paper this comparison has always been in the favour of hydro -power, the Krafla project being an exception.

The success at Svartsengi has done alot of good for the geothermal industry in Iceland. It has provided the counterbalance to Krafla and shown that high-temperature geothermal energy is viable and that Námafjall is not the exception. The novelty of the Sudurnes Regional Heating power plant has created great interest and for the first time in

Iceland has there been generated electric power and thermal power in the same plant. Co-generation will undoubtedly be widely practiced in the power and processing plants built in future.

For many years there have been plans to build a sea-chemicals complex at the Reykjanes high-temperature area (Lindal 1975). In the last few years pilot plant studies have been carried out to investigate the production of salts (mainly sodium chloride NaCl) from the geothermal brine itself. It has now been decided to build a small plant that will produce about 7000 tonnes/year of common salt to be used in the fishing industry mainly. If this operation turns out to be successful then a 40,000 tonnes/year plant will perhaps be built. In the plans for this larger plant there are provisions for 5-10 MW-electrical back pressure turbine in an arrangement similar to the one at Svartsengi.

In the long range planning for the Reykjavík District Heating Service, there are plans for a thermal power plant to be located in the Hengill high-temperature area (Zoëga 1974). The basic concept is similar to the one at Svartsengi. In the years 1965-1975 five boreholes were drilled in the Nesjavellir field of the Hengill area. These were exploration boreholes mainly but one of them is a production hole. The pilot studies carried out at Svartsengi and described above, were later repeated in Nesjavellir. Last year the Reykjavík District Heating Servisce, which owns the Nesjavellir field, installed a small back-pressure steam turbine at the site of the former pilot plant. It is an Elliott DYR-UG turbine -generator 338 kW (name-plate capacity) using 6 bar-a steam. It has one Curtis wheel and is 3000 rpm. This unit is almost identical to the auxhiliary steam turbine-generator in the Krafla Power Station. The purpose of operating this small unit is both to gain experience in the Nesjavellir field and to provide electric power for the development work the Reykjavík District Heating Service hopes to carry out in the next few years. The unit was commissioned in September 1980 and has operated continuously since then.

In Hveragerdi, the cradle of high-temperature geothermal energy utilization in Iceland, many schemes have been put foreward to harness the

steam already available from the boreholes drilled about 20 years ago. Two of the wells are used for the Hveragerdi district heating service (see above) while the others are idle. The main interest has been to use the boreholes for heating greenhouses and even generating electricity for antificial lighting (Lúdvíksson). In a country with a climate like Iceland's, this concept has received alot of attention. Some research and development work has been carried out on the effect of artificial light on plant growth, but as yet the concept has not been shown to be economical. The commercial reason for this scheme has been the export of flower seedlings to the continent of Europe.

In January 1973 there was a volcanic eruption on the island of Heimaey, where more than 5000 people live (Vestmannaeyjar). The inhabitants were evacuated and the lava flowed over parts of the town. When the volcanic activity ceased the following year the town was rapidly re-built and became again one of the most important fishing port in Iceland. In the true pioneering spirit of people fighting volcanoes, there was built a district heating system harnessing the heat of the lava. Fresh water is sprayed over the lava field and percolates 10-20 m down to the interface of the molten lava which is about 1000°C. Steam is formed and rises to the surface where it is collected and used at near 100°C in heat exchangers to heat the circulating district heating water. The "lava heat" thus used amounts to about 10 MW-thermal. The system could be desribed as hot-dry-rock and should perhaps be included in our perspective of geothermal electric power developements in future.

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TABLE 1

Main conclusions of the assessment of high-temperature geothermal areas in Iceland. Known areas 1-19, potential areas 20-28 (Pálmason, 1981).

Name	A (km^2)	B$\times10^{-18}$ (J)	C (-)	D$\times10^{-18}$ (J)	E (MW_e)
1. Reykjanes	2	2.4	1.0	0.5	28
2. Svartsengi	11	10.7	1.0	2.1	108
3. Krísuvík	60	42.6	0.8	6.8	302
4. Brennisteinsfjöll	2	1.9	0.6	0.2	12
5. Hengill	100	97.0	0.7	13.6	689
6. Geysir	3	2.9	0.9	0.5	27
7. Kerlingarfjöll	11	10.7	0.7	1.5	76
8. Hveravellir	1	1.0	0.9	0.2	9
9. Mýrdalsjökull	?	?	0	0	0
10. Torfajökull	140	135.8	0.7	19.0	964
11. Grímsvötn	65	63.1	0	0	0
12. Köldukvíslarbotnar	8	7.8	0.8	1.2	63
13. Vonarskard	11	10.7	0.6	1.3	65
14. Kverkfjöll	25	24.3	0.2	1.0	49
15. Askja	25	24.3	0.3	1.5	74
16. Fremrinámar	4	3.9	0.9	0.7	35
17. Námafjall	7	8.5	0.9	1.5	88
18. Krafla	30	36.6	0.9	6.6	376
19. Theistareykir	19	18.4	0.8	2.9	150
20. Prestahnúkur	1	1.0	0.5	0.1	5
21. Hofsjökull	?	?	0	0	0
22. Tindafjallajökull	1	1.0	0.1	0.1	1
23. Blautakvísl	7	6.8	0.7	1.0	48
24. Thórdarhyrna	?	?	0	0	0
25. Hrúthálsar	7	6.8	0.9	1.2	62
26. Gjástykki	7	6.8	1.0	1.4	69
27. Axarfjördur	30	29.1	0.9	5.2	266
28. Kolbeinsey	?	?	0	0	0
Total (average)	~600	-	(~0.6)	~70	~3,500

For explanations see following page.

Explanations of symbols in Table 1.

A: Size of area km^2 based on surface manifestations and resistivity surveys.

B: Energy content $x10^{-18}$J of rock and water above 130°C, down to a depth of 3 km.

C: Accessability judged from topography and general features of surroundings.

D: Available energy $x10^{-18}$J. Geothermal recovery factor assumed 0.2 (20%).

E: Available electric power MW_e for 50 years assuming ~8% conversion efficincy.

a: Includes Svartsengi and Eldvörp.

b: Includes Krísuvík, Trölladyngja and Sandfell.

c: Includes Hengill, Nesjavellir and Hveragerdi.

TABLE 2

Energy delivered to consumers in Iceland 1979 (Orkumál).

Sector	Energy source (TJ)			
	Hydro	Geothermal[a]	Oil	Total (%)
Residential[b]	876	15	16	907 (1.8)
Space heating[c]	1,353	17,255	4,155	22,763 (44.6)
Industry	6,141	2,129[d]	5,924	14,194 (27.8)
Fisheries	-	-	6,869	6,869 (13.5)
Commercial	587	10	11	608 (1.2)
Transport	-	-	5,681	5,681 (11.1)
Total (%)	8,957 (17.6)	19,409 (38.0)	22,656 (44.4)	51,022 (100.0)

a: Thermal energy above 5°C and 46 GWh of electricity.

b: General domestic use of electricity.

c: Heating of residential, commercial and industrial buildings.

d: Drying operations and greenhouses.

TABLE 3

Low-temperature geothermal energy used in Iceland in 1980 (Gudmundsson & Pálmason 1981).

Type of use	(%)[b]	Thermal power (MW) >5°C	>15°C	>35°C
Space heating[a]	89.2	959.3	850.1	634.4
Greenhouses	5.4	59.6	51.6	35.6
Swimming pools	3.2	35.4	30.8	21.3
Industrial drying	1.9	20.2	18.3	14.5
Fish culture	0.3	6.9	3.2	2.1
Total	100.0	1081.4	954.0	707.9

a: Residential, commercial and industrial buildings.

b: Calculation based on >15°C values.

TABLE 4

High-temperature geothermal energy used in Iceland in 1980.

Name of area	Boreholes		Thermal power (MW)		Electric Power
	Drilled	Production	Installed[a]	Used	(MW)
Svartsengi	10	9	520	50[b]	8
Hengill	>25	19	135	25[b]	0
Námafjall	12	3	100	35[a]	3
Krafla	15	8	140	0	30
Total	>62	39	895	110	41

a: Above 100°C condensate.

b: Space heating above 35-40°C.

TABLE 5

Approximate thermal power used in 1980 in Iceland from low- and high-temperature geothermal areas. The steam used for geothermal electric power generation is not included in this tabulation.

Type of use	Thermal power >35°C (MW)			(%)
	Low	High	Total	
Space heating	634	60	694	84.9
Greenhouses	36	15	51	6.2
Swimming pools	21	0	21	2.6
Industrial	15	35	50	6.1
Fish culture	2	0	2	0.2
Total	708	110	818	100.0

TABLE 6

Main technical specifications of geothermal electric power stations in Iceland (Thórhallsson et al. 1979).

Specification	Námafjall	Krafla	Svartsengi	Svartsengi
Manufacturer	BTH	MHI	AEG-KANIS	Fuji
Installed (year)	1968	1978	1978/1979	1980
Rated capacity (MW)	3	30	2 x 1	6
Speed (rpm)	3000	3000	4479	3000
Inlet pressure (bar-a)	9-10	7.2/2.0	5.4	5
Steam flowrate (kg/s)	~14	53.2/19.6	8.9	37.2
Exhaust pressure (bar-a)	~1.1	0.12	1.7	1.2
Type/Stages	C	5	C	C

TABLE 7

Electricity production in geothermal power stations in Iceland (Orkumál).

Station	-	1975	1976	1977	1978	1979	1980
Námafjall	A	3/3	3/3	3/3	3/3	-	2/3
(1969)	B	18,347	19,012	16,125	5,826	-	2,393
	C	6,116	6,337	5,375	1,942	-	-
Krafla	A	-	-	-	6/30	6/30	12/30
(1978)	B	-	-	-	12,459	41,962	37,453
	C	-	-	-	2,077	6,994	-
Svartsengi	A	-	-	-	1/1	2/2	8/8
(1978/1979/1980)	B	-	-	-	-	6,737*	9,739*
	C	-	-	-	-	-	-
Total (MWh)	-		19,012	16,125	18,285	48,709	49,585

A: Approximate maximum load/name plate capacity.

B: Total generation of electricity MWh.

C: Utilization time, hours.

*: Includes own use ~50 %

TABLE 8

Estimated non-condensable gas composition in geothermal steam (Compiled by G. Gíslason & T. Hauksson).

Concentration (mg/kg)	Námafjall	Krafla	Krafla	Svartsengi
Borehole number	N-11	K-9	K-14	S-6
Date of sample	20.09.80	25.11.80	28.11.80	15.05.80
Enthalpy mixture (kJ/kg)	2,355	1,055	2,634	1,030
Steam fraction	0.79	0.15	0.93	0.18
Temperature[a] (°C)	180	175[b]	175[b]	155
CO_2	799	18,080	11,660	2,540
H_2S	1070	642	751	34.5
H_2	93	6.4	35.9	0.03
CH_4	1.17	6.6	0.84	0.50
N_2	5.8	0.0	0.0	33.6
Total	1,969 (~0.2%)	18,735 (~1.9%)	12,448 (~1.2%)	2,609 (~0.3%)

a: Temperature corresponding to saturation pressure of steam-water separation.

b: Separators are presently operated at 6-7 bar-a but not the design pressure 8-9 bar-a.

TABLE 9

The total cost of drilling a 1923 m deep borehole in Námafjall in 1979. Drilling time 33 days. Drillrig Gardner Denver 700 E (Ragnars & Benediktsson 1981).

Item	U.S dollars	(%)
Drill-site preparation, roads, cable-tool work.	33,800	4.8
Bits, reamers, centralizers, casing shoes, cement, mud.	35,400	5.0
Casings and valves	138,700	19.8
Transport of cement and supplies, logging.	110,600	15.7
Drilling, rent, fuel, wages, maintenance, fares.	220,200	31.4
Transport of rig	72,000	10.2
Miscellaneons	92,000	13.1
Total	702,700	100.0

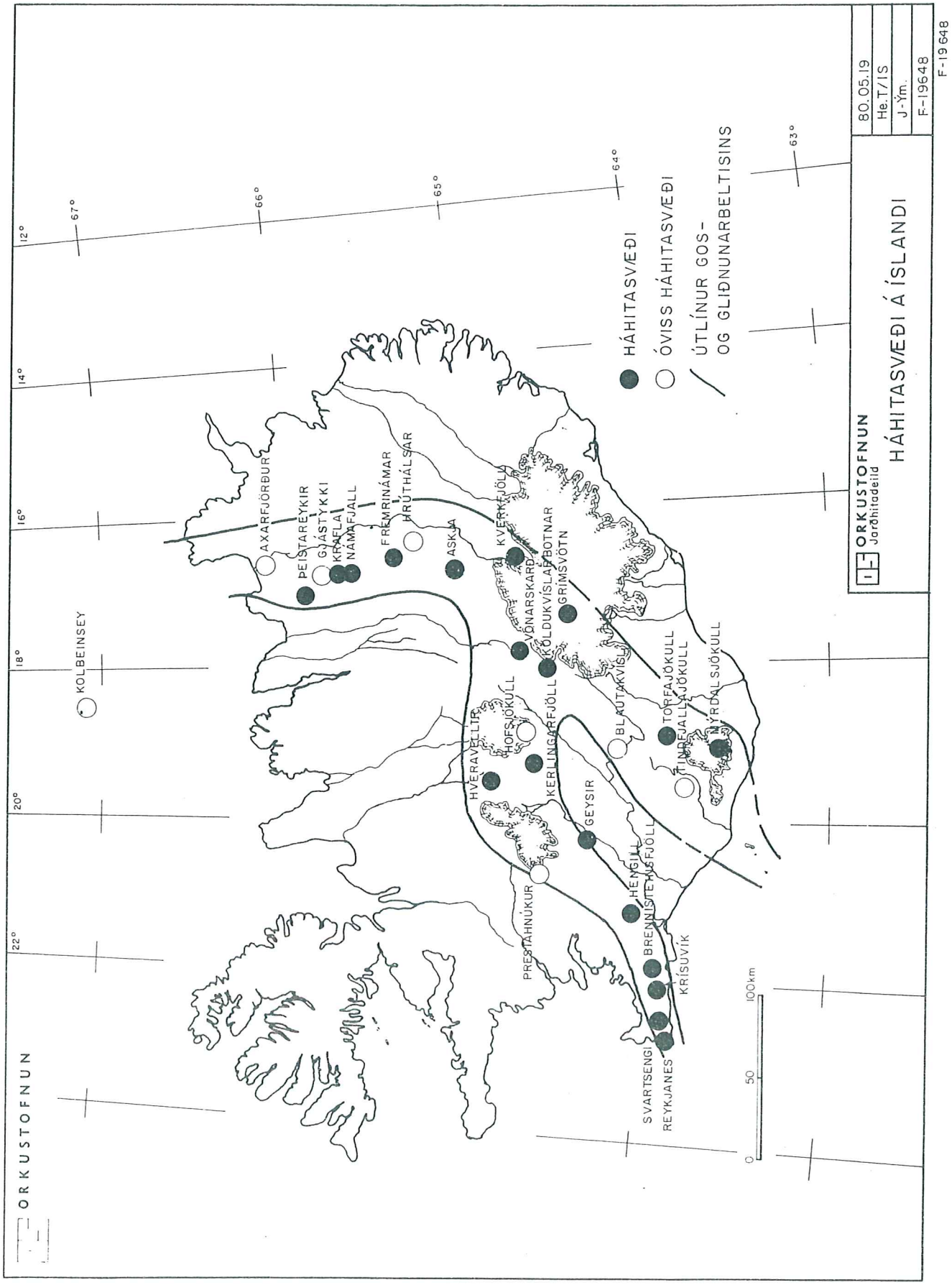
TABLE 10

The total cost of drilling a 1604 m deep borehole in Svartsengi in 1979. Drilling time 35 days. Drillrig Oliwell 52. Casing program: Production 13 3/8" (68 lb/ft) to 600 m, liner 9 5/8" (43 lb/ft) to bottom.

Item	U.S dollars	%
Drill-site preparation and cellar.	11,300	2.0
Pre-drilling (cable-tool rig)	25,400	4.6
Rig rental	89,750	16.1
Labour (rig crew)	74,400	13.3
Meals	8,100	1.5
Transportation (rig & crew)	43,590	7.8
Drill-bites and reamers	35,900	6.4
Drilling mud	8,500	1.5
Tool rental	8,200	1.5
Sales tax	38,500	6.9
Logging and geology	18,400	3.3
Casing 13 3/8" and 9 5/8"	114,500	20.6
Casing hardware[a]	12,400	2.2
Slotting of liner	34,000	6.1
Well-head and valve	13,100	2.3
Cement and silica flour	13,100	3.9
Total	558,040	100.0

a : Hanger, shoes, centralizers.

Figure 1.


ORKUSTOFNUN
Jarðhitadeild
HÁHITASVÆÐI Á ÍSLANDI
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ÓVISS HÁHITASVÆÐI
ÚTLÍNUR GOS- OG GLIÐNUNARBELTISINS
12°
14°
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22°
67°
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65°
64°
63°
AXARFJÖRÐUR
KÓLBEINSEY
ÞEISTAREYKIR
GJÁSTYKKI
KRÍSUVÍK
NÁMAFJALL
FREMRINÁMAR
BRÚTHÁLSAR
ASKJA
KVERKFJÖLL
VÖNARSKARÐ
KÖLDUKVÍSLARBOTNAR
GRÍMSVÖTN
BLAUTAKVÍSL
TORFAJÖKULL
TINDFJALLAJÖKULL
NÝRDALSJÖKULL
HOFSJÖKULL
HVERAVELLIR
KERLINGARFJÖLL
GEYSIR
HENGILL
BRENNISTEINSFJÖLL
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KRÍSUVÍK
SVARTSENGI
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ORKUSTOFNUN

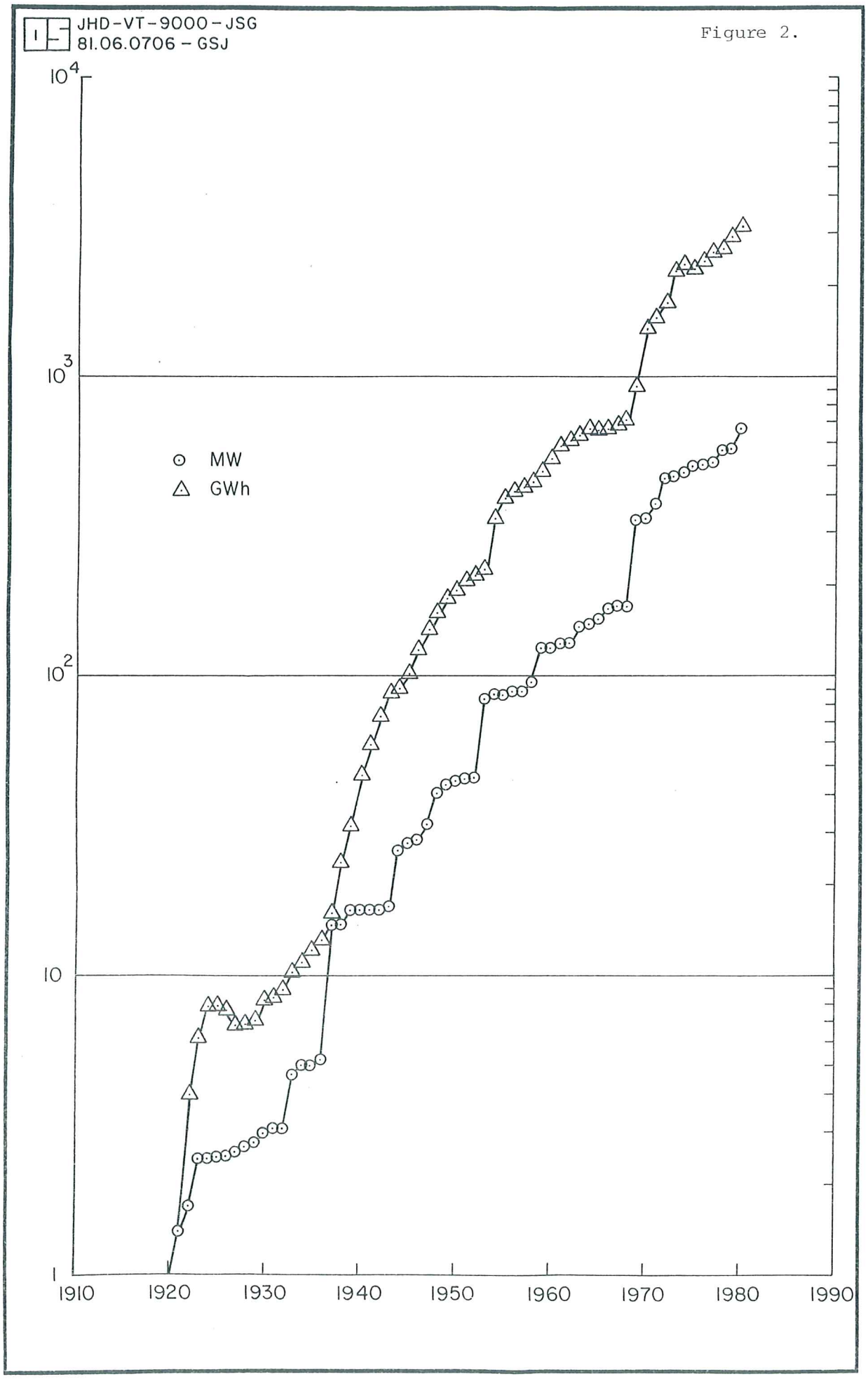

JHD-VT-9000-JSG
81.06.0706 - GSJ
Figure 2.
10^4
10^3
10^2
10
1
MW
GWh
1910
1920
1930
1940
1950
1960
1970
1980
1990

Figure 3.

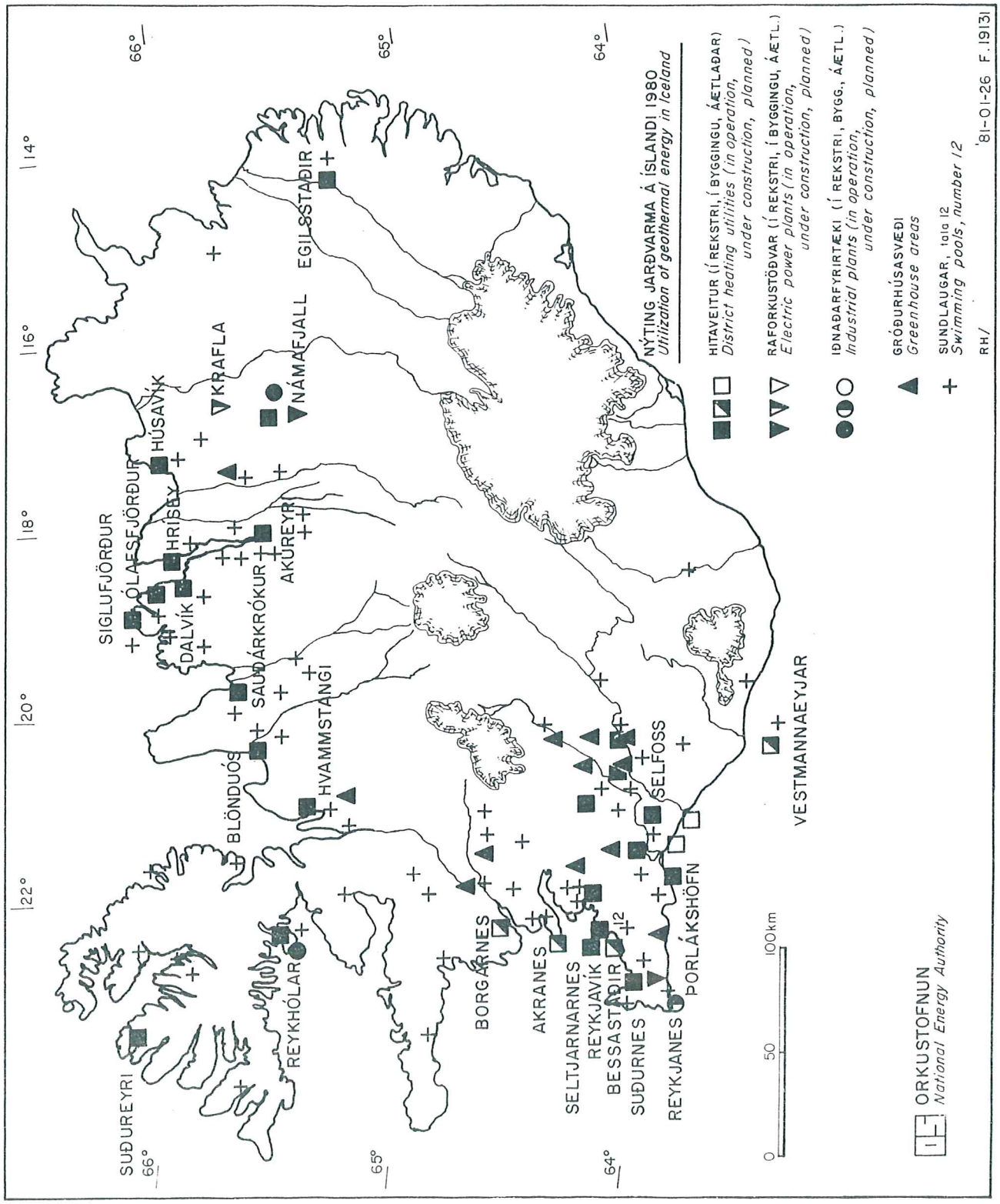
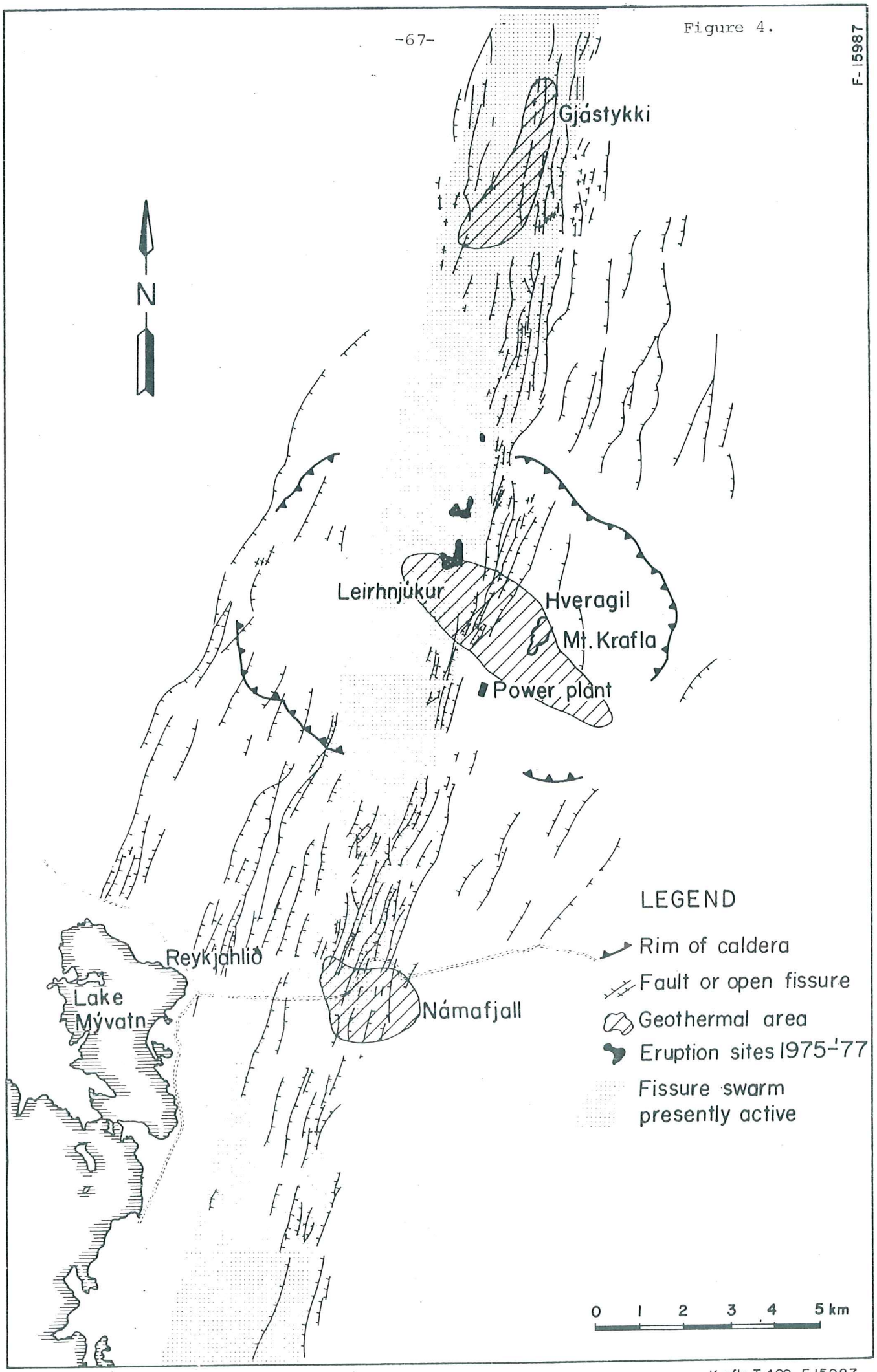

NÝTING JARÐVARMA Á ÍSLANDI 1980
Utilization of geothermal energy in Iceland
HITAVEITUR (Í REKSTRI, Í BYGGINGU, ÁÆTLAÐAR)
District heating utilities (in operation, under construction, planned)
RAFORKUSTÖÐVAR (Í REKSTRI, Í BYGGINGU, ÁÆTL.)
Electric power plants (in operation, under construction, planned)
IÐNAÐARFYRIRTÆKI (Í REKSTRI, BYGG., ÁÆTL.)
Industrial plants (in operation, under construction, planned)
GRÓÐURHÚSASVÆÐI
Greenhouse areas
SUNDLAUGAR, tala 12
Swimming pools, number 12
RH/
81-01-26 F.1913
ORKUSTOFNUN
National Energy Authority
0
50
100km
66°
65°
64°
22°
20°
18°
16°
14°
SUÐUREYRI
REYKHÓLAR
BLÖNDUÓS
SIGLUFJÖRÐUR
ÓLAFSFJÖRÐUR
DALVÍK
HÚSAVÍK
HRÍSEY
SAUÐÁRKRÓKUR
HVAMMSTANGI
KRAFLA
NÁMAFJALL
AKUREYRI
EGILSSTAÐIR
BORGARNES
AKRANES
SELTJARNARNES
REYKJAVÍK
BESSASTAÐIR
SUÐURNES
REYKJANES
ÞORLÁKSHÖFN
SELFOSS
VESTMANNAEYJAR

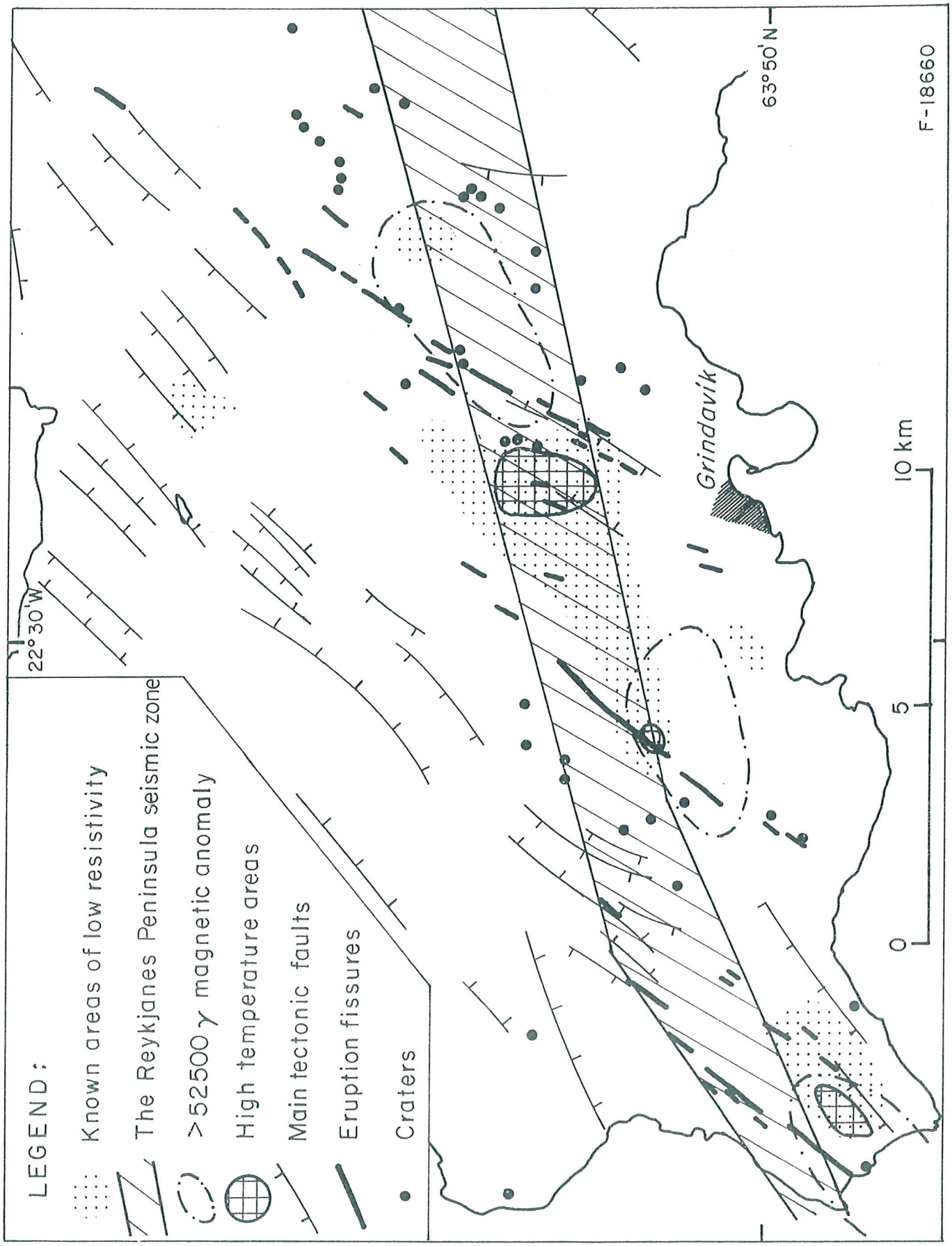
Figure 4.



'7707.29 AB/AÁ

Krafla T 409 F 15987

Figure 5.


LEGEND:
Known areas of low resistivity
The Reykjanes Peninsula seismic zone
>52500 γ magnetic anomaly
High temperature areas
Main tectonic faults
Eruption fissures
Craters
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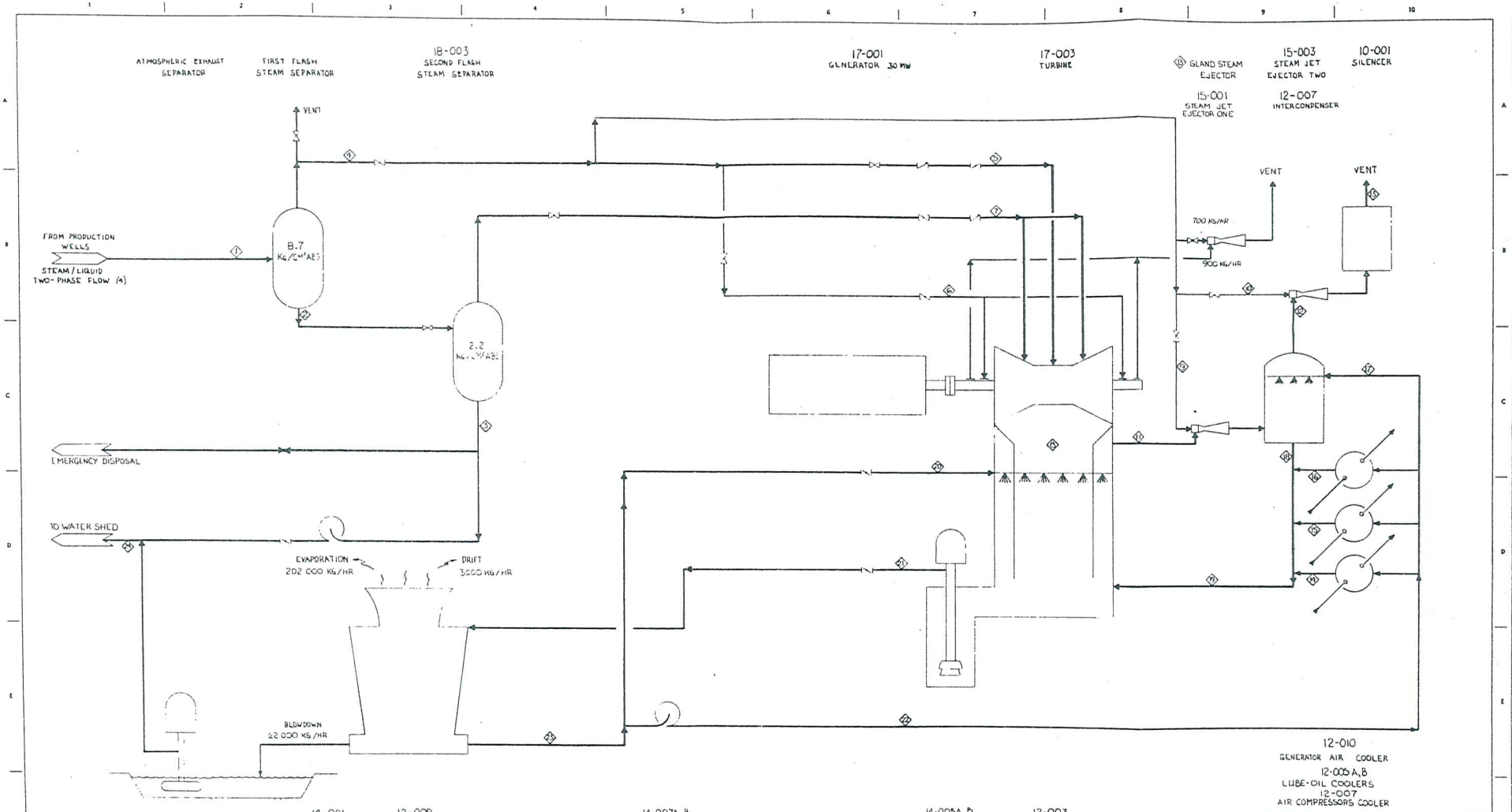
63°50'N
Grindavik
0
5
10 km
F-18660



STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
STEAM FLOW (KG/HR)	915 000			203 100	191 500	1600	75 500	262700	5000	4300	400	100	4400											
WATER FLOW (KG/HR)		711 900	641 000	-	-	-	-		-	-	-	-	-	3000	90 000	165 000	135 000	140 000	398 000	5561000	6221 000	393 000	5954000	
NON-CONDENSABLE GAS FLOW (KG/HR)	2100	-0-	-0-	2100	1990	20	-0-	2000	50	40	1990	2040	2080											
AIR FLOW (KG/HR)											200	200								130				
TEMPERATURE (°C)	172.2	172.2	122.9	173.2	165.1	165.1	119.7	49.2	165.1	165.1	25	25	—	32	24.9	26.1	22	46.0	32.9	22	45.2	22	22	
PRESSURE (KG/CM² ABS.)		8.7	2.2	8.7	7.2	7.2	2.0	—	7.2	7.2	—	—	—											
PRESSURE (MM HG ABS.)	—	—	—	—	—	—	—	89	—	—	87	280												
ENTHALPY (KCAL/KG)	285.1	175.1	123.2	661.1	659.7	659.7	646.2	554.9	659.7	659.7				32	25.0	26.2	22	46.0	32.9	22	45.2	22	22	
DENSITY (KG/M³)	19.6		940.5		3.68		1.111	0.0800 (5)						995	997	997	998	990	995	998	990	998	998	

- NOTES -

1. FLOW QUANTITES ARE GIVEN FOR ONE 30 MW UNIT AT GUARANTEED THROTTLE FLOW CONDITIONS.
2. ASSUMED DOWNHOLE EFFECTIVE TEMPERATURE: 270°C.
3. ASSUMED NONCONDENSABLE GASES QUANTITY: 0.23% (BY WEIGHT) OF GEOTHERMAL WELL WATER FLOW.
4. STEAM SEPARATOR AND STEAM LINE PRESSURES ARE FOR STEAM ONLY — PARTIAL PRESSURE OF NON-CONDENSABLE GASES NOT INCLUDED.
5. DENSITY GIVEN FOR STEAM ONLY.
6. ASSUMED EFFICIENCIES
   TURBINE THERMAL EFF: 75.5%
   TURBINE MECHANICAL EFF: 99.0%
   GENERATOR EFF: 97.4%
7. ASSUMED CONDENSER AIR LEAKAGE: 70 KG/HR.
8. TURBINE-GENERATOR WILL PRODUCE APPROX. 35 MW WITH GREATER WELL FLOW AND INCREASED STEAM AND CONDENSER PRESSURES.

REFERENCE DRAWINGS

REV.	ZONE	DATE	REVISION	DR.	CHK.	APPR.
A		1/20/74	ADDED GLAND STEAM EJECTOR REVISED FLOW DATA FINAL REPORT ISSUE			
B		1/4/74	ISSUED FOR REVIEW			

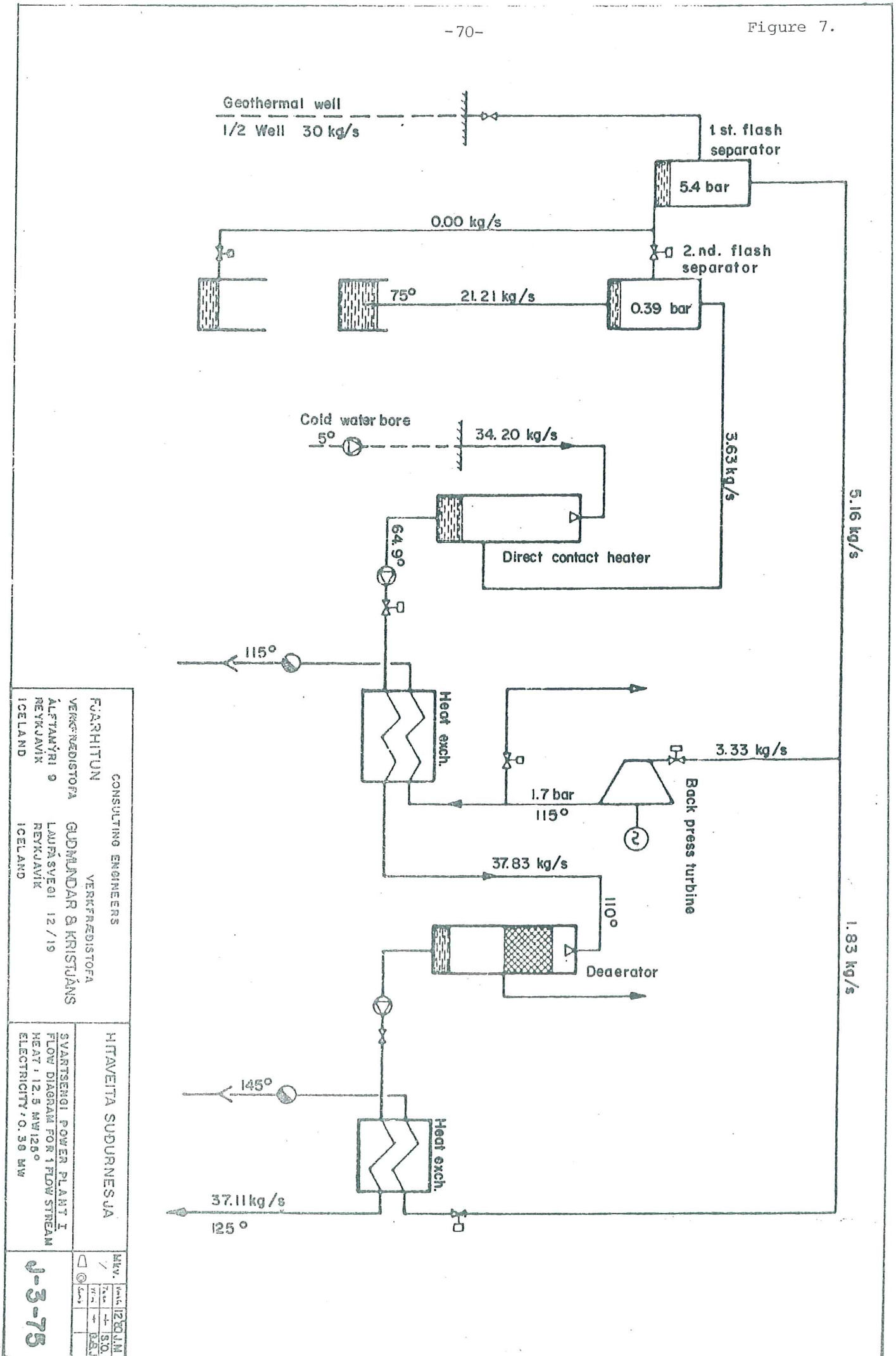
CONSULTING ENGINEERS
ROGERS ENGINEERING CO., INC.
SAN FRANCISCO, CALIFORNIA
THORSEN AND PARTNERS
BYLLYNE, IDAHO
SCALE NONE
DATE 12/31/73
DR. CHK. ENG. APPROVED

KRAFLA PROJECT EXECUTIVE COMMITTEE
KRAFLA GEOTHERMAL PROJECT
APPROVALS

FLOW DIAGRAM
DOUBLE-FLASH STEAM CYCLE
KRAFLA GEOTHERMAL POWER PLANT
UNIT 1 30 MW
JOB No. S-74028
A1-02-001 B

Figure 6.

Figure 7.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1 st. flash separator
5.4 bar
0.00 kg/s
2.nd. flash separator
75°
21.21 kg/s
0.39 bar
Cold water bore
5°
34.20 kg/s
3.63 kg/s
5.16 kg/s
64.9°
Direct contact heater
115°
Heat exch.
3.33 kg/s
1.7 bar
115°
Back press turbine
37.83 kg/s
110°
Deaerator
1.83 kg/s
145°
Heat exch.
37.11 kg/s
125°
CONSULTING ENGINEERS
FJARHITUN
VERKFRÆDISTOFA
ÁLFTAMÝRI 9
REYKJAVÍK
ICELAND
VERKFRÆDISTOFA
GUÐMUNDAR & KRISTJÁNS
LAUFÁSVEGI 12/19
REYKJAVÍK
ICELAND
HITAVEITA SUÐURNESJA
SVARTSENGI POWER PLANT I
FLOW DIAGRAM FOR 1 FLOW STREAM
HEAT : 12.5 MW 125°
ELECTRICITY : 0.38 MW
J-3-75

JHD-VT-9000
81.06.0739

Figure 8.